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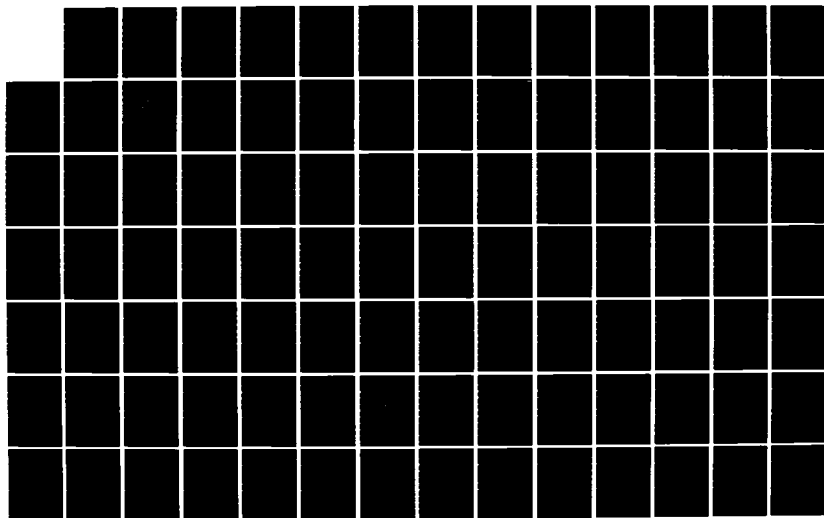
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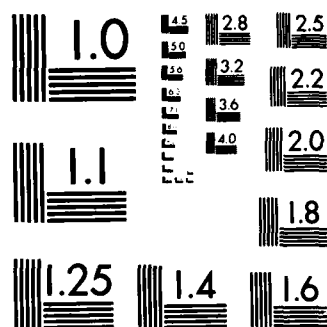
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The literature concerning the resting point for accommodation was reviewed. The physiological and anatomical evidence supporting an intermediate resting position were covered in sufficient detail to provide a context within which the behavioral evidence could be interpreted. The more recent behavioral research provides strong evidence for the intermediate resting position and its pervasive effects on visual information processing.

The present study investigates the possible development of a functional metric for the description of stimuli, the effects of varying quantities of

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interposed texture on the accuracy of accommodation to an adequate target at different optical distances, and shifts in apparent size coincident with changes in accommodation.

A functional metric based on the slope of the regression line relating accommodation to stimulus presentation distance appears feasible. Further development would be required employing a wider range of objective stimulus characteristics. As stimulus adequacy (indexed by this functional metric and percent contrast) declined, the ability of these stimuli to influence accommodation away from targets presented at various optical distances declined. The disruption of accommodation is apparently related to stimulus adequacy. For the most adequate interposed stimuli disruption was greatest at the resting position for accommodation known as the dark focus (the plane of focus assumed by the eye in the dark). Judgments of apparent size are related to accommodation. Nearer accommodation generally resulted in judgments of diminished apparent size and farther accommodation generally resulted in judgments of increased apparent size. These judgments were verified through quantitative measurement of apparent size.

The implications of this for vehicle control and within other applied settings are manifold. Automobile and aircraft operation are heavily dependent on accurate perception of size and distance. Moreover, observation is inevitably through a surface. Possible effects of misperceived size are discussed.

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Technical Report

BEL-79-1/AFOSR-79-5

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VISUAL ACCOMMODATION, THE MANDELBAUM EFFECT, AND APPARENT SIZE

Russell A. Benel



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## INTRODUCTION

This distinction between visual space and true space--between objects as they are spatially and as they appear to us visually must be made by all means, and must be made entirely clear to us if we are to gain proper insight into the laws of vision.

(Hering, 1879/1942, p. 1)

Failure to consider the implications of Hering's remarks can lead the designer of visual displays to inappropriate application of some so-called laws of vision. As Ogle (1950) has suggested the objective and subjective worlds are incommensurate. Although this may be a slight overstatement, it is true that the geometric laws of Euclid hold for objective space, whereas for visual space this is not true (Westheimer, 1978). Even in more quotidian circumstances, geometric principles do not adequately predict the subjective appearance of objects. The classical view of the relationship between the objects and their appearance has assumed certain attributes of the visual system.

Recent evidence has made it clear that earlier conceptions of visual functioning bear reexamination. Roscoe and Benel (1978) have noted two misconceptions that have misdirected psychologists for more than a century. The first concerns the misbelief that the eye's relaxed accommodation distance is at the far point, for the emmetrope at



"optical infinity." This legacy has been passed down from Helmholtz (1867/1962, vol. 1, p. 360) who declared "when it [the eye] is focused for the far point, ... accommodation, therefore, is relaxed." Concomitant with this view is a single innervation theory of control of the ciliary muscle. Frequently, belief in single innervation obscured the need for verification of the far resting point and vice versa.

The second closely related misconception has been the belief that the eye reflexively accommodates accurately to the distance of an object present in foveal vision. This latter belief is often implicitly assumed to hold in laboratory experiments on visual sensation and perception. The importance of these topics is apparent to psychologists because of their historical concern for the role of oculomotor adjustments in space perception (Baird, 1970). These oculomotor adjustments represent the initial response to distance and determine the clarity of the retinal image. This, in turn, has a fundamental influence on perception and on the information derived from the stimulus.

The relationship between the actual accommodative state and the apparent size of objects can be dramatically illustrated by a simple demonstration:

... Look with one eye, while the other is closed, at a window several meters away. Then hold one finger so close in front of the active eye that you have to

accommodate on it with difficulty. As soon as this is done, the window shrinks and seems smaller than when one observes it without the effort of accommodation. Of course, a measuring rod behaves in precisely the same way if it is applied to the window at that time. Thus, the objective size of the window gives us no information as to the subjective size, either of the measuring rod or of the object--the window--that it measures. The spatial extent of objects does not give us any standard for the size of subjective, visual objects. (Hoffman, translated in Ogle, 1950, p. 10)

Distant objects are often viewed through an intervening surface. A particularly relevant phenomenon, first documented by Mandelbaum (1960), concerned an inability to resolve the contours of a distant skyline when they are viewed through a window screen. A subsequent informal experiment indicated that the phenomenon was related to an involuntary accommodation to the screen. If intervening resolvable texture can cause inappropriate near accommodation, then it follows from Hoffman's demonstration that the apparent size of distant objects of a fixed retinal angle may differ from those viewed without such texture.

The implication of this for vehicle control and within other applied settings are manifold. The current research is directed toward determining the nature of the relationship between apparent size and

accommodation both with and without interposed texture, the apparent magnitude of such effects in relation to individual differences, and a quantification of shifts in apparent size with accommodative "trapping." Evidence surrounding the previously mentioned misconceptions will be reviewed to provide a context within which the "Mandelbaum effect" may be understood. The recent evidence from Owens (1976; 1979) on the stimulus variables involved will be reviewed because it is indicative of the potency of the effect and importance of individual differences.

## THE PHYSIOLOGICAL RESTING POSITION OF ACCOMMODATION

One of the longest standing unresolved issues in the area of visual physiology concerns the physiological resting position of accommodation and concomitantly the mechanism for the far accommodative response of the lens. The history of the role of the sympathetic nervous system (SNS) has been that of proposal and denial of its active participation in accommodation. All current and historically important textbooks in opnthalmology document the role of the parasympathetic nervous system (PNS) in active near accommodation (e.g., Davson, 1972; Duke-Elder, 1940). However, Alpern (1962, p. 219) characterizes the prevailing caution toward the importance of the SNS in accommodation by titling his discussion of the subject, "Possible sympathetic innervations."

### History

Warwick (1954) points out that as early as 1722 accounts were given of the ciliary nerve distribution of the eyeball. In 1823 stimulation of the ciliary nerve (discussed in Pitts, 1967) was shown to produce pupillary dilation. Recognition of the relation of the ciliary nerve to both pupillary response and accommodation led Helmholtz to consider the possibility of dual innervation of the ciliary muscle. Helmholtz

(1866/1962) discredited the idea for two reasons: (1) the muscle fibers were so intertwined as to lead him to conclude discrete actions were impossible and (2) atropine paralyzed the ciliary muscle without change in the refractive condition of the eye. Cogan (1937) who faulted these arguments cited the apparent complexity of both the intestine and the uterus as evidence against the former and questioned whether atropine does in fact paralyze the entire muscle and not just that portion which is under PNS control.

Henke (1860; in Cogan, 1937) postulated that the circular fibers of the ciliary muscle function near accommodation while the longitudinal are for distance. Warlomont (1875; in Cogan) performed an anatomic study of the ciliary muscle and reiterated Henke's hypothesis. Warlomont also questioned the application of the terms passive and/or negative accommodation with reference to distant vision. Jessop (1866; in Pitts, 1967) stimulated the long ciliary nerves and used Purkinje-Sanson images (reflections from the anterior and posterior surfaces of the cornea and lens) to measure distant accommodation. (See Boring, 1942, for an extended treatment of the history of these images.) Jessop (cited in Alpern, 1962) also reported instillation of cocaine into the eye resulted in relaxation of the ciliary muscle. Morat and Doyon (1891; in Alpern) observed a similar lens flattening effect from stimulation of the cervical sympathetic nerve.

Henderson (1926), apparently unaware of Morat and Doyon, proposed dual innervation noting that the ciliary muscle was the only smooth

muscle thought to have only one innervation (the third cranial nerve). It is, however, not at all clear that he viewed these as active antagonistic processes. He referred to the SNS fibers as postural, being used to fix accommodation induced by the PNS. Possibly the most influential paper (certainly one of the most widely cited by dual-innervation proponents) was that of Cogan (1937). Cogan reviewed the literature on SNS control of accommodation, discussing much of the above literature, and presenting clinical, experimental, and pharmacological evidence for his view.

The more contemporary literature cited by Cogan is instructive for carrying the flavor of the argument concerning PNS control alone versus PNS plus SNS control. Cogan reported that Hudelo considered antagonistic innervation to be necessary for understanding the rapidly occurring refractive changes seen in some clinical populations. A strong opponent of this position was Luedde (1932) who stated that it seemed unlikely that the mechanical readjustment of tissues incident to distant accommodation depended upon SNS innervation. Luedde also provided critical appraisal of Cogan's hypothesis in the discussion following that paper.

Although much has been accomplished in the interim, the essence of these two opposing positions remains. On the one hand there are those who believe it is necessary to look for dual innervation with antagonistic, opposing actions, and at the other extreme, the single innervation PNS believers. As with other dichotomous arguments, it is

not long before someone jumps in the breach with a theory that attempts to reconcile the extremes. In the course of the discussion of the anatomical data the middle ground will be explored. As a brief preview, Genis-Galvez (1957) noted the existence of the SNS fibers, but questioned the necessity for them to set up an antagonism with the PNS fibers.

#### Anatomy and Physiology

Assuming for the moment that an SNS input does affect accommodation, there are two viewpoints concerning the nature of the SNS effect. According to Morgan (1946), flattening of the lens results from vasoconstriction of the blood vessels of the ciliary body. The reduced vascular bed also reduces the mass of the ciliary body thereby increasing the tension on the fibers of the zonule which flattens the lens. In enucleated eyes (divorced from the circulatory system), flattening of the lens may also be achieved through stimulation of the sympathetic effectors by drugs (Meesman, 1952) or by electrical stimulation of the long ciliary nerves (Melton, Purnell, & Brecher, 1955). The critical questions are whether neither, either, or both of the mechanisms operates and how to evaluate the relevance of the experimental findings under varying conditions.

Cogan (1937) reviewed the anatomy surrounding the lens and divided the muscle fibers of the ciliary into three groups according to their direction: (1) the circular fibers--concentric with the lens; (2) the radial fibers--radiating fan-wise to the ciliary body; and (3) the meridional fibers--originating at the scleral spur extending toward the choroid. The groups, especially the former two, are closely intertwined. Figure 1 illustrates these divisions. Cogan interpreted the design of the structure to indicate that the circular fibers will tend, on contraction, to release tension on the zonule, thereby allowing the lens to increase in curvature. Although the action of the radial fibers was thought to be complex, they could exert a forward and outward pull whereby the anterior displacement is overbalanced by the outward movement, increasing the zonular tension and flattening the lens. In this way, according to Cogan, the radial muscles are responsible for distant accommodation.

Despite the speculative nature of this explanation, the dual innervation theory struck a responsive chord in many researchers. Bielschowsky (from the discussion of Cogan, 1937) reported that he had been considering this problem for many years and had raised this question in 1900 at the meeting of the Heidelberg Ophthalmologische Gesellschaft. Gullstrand had apparently rejected his argument by fiat. However, Bielschowsky went on to note that, as early as 1856, von Graefe had found it improbable that accommodative changes were the result of a single nerve. The evidence from Poos was also cited by Bielschowsky for



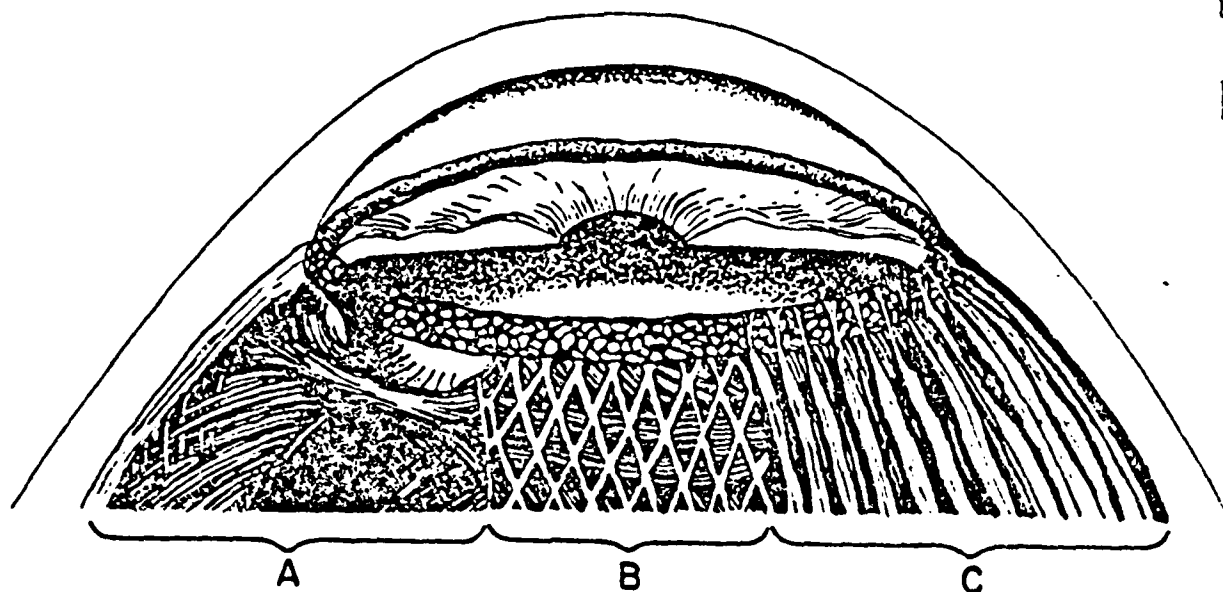


Figure 1. Schematic diagram illustrating the three divisions of the ciliary body. (A) Circular fibers; (B) radial or reticular fibers; (D) longitudinal fibers. (after Coleman, 1970)

its support of the dual innervation hypothesis. In 1928, Poos reportedly performed pharmacologic stimulation of SNS and PNS nerve endings, and his results were consistent with dual innervation. Despite this evidence, Bielschowsky cautioned against interpreting this in terms of an independent action of part of the ciliary muscle.

In a series of papers Morgan and Olmsted (1939), Olmsted and Morgan (1939), and Morgan, Olmsted, and Watrous (1940) demonstrated rather

convincingly that there is sympathetic input that is responsible for at least a portion of distant accommodation. In 1941, Olmsted and Morgan attempted to demonstrate changes in lens curvatures through the venerable technique of Purkinje image photography. Unfortunately their photographs did not permit reproduction, and they were reduced to providing outline tracings of the photographs. In the tracings one and only one image changed and this was the third Purkinje image (from the anterior surface of the lens).

For further evidence, they performed partial iridectomy on cats and photographed the lens directly showing a distinct flattening of the lens consistent with distant accommodation. The photographs also revealed a forward movement of the anterior lens surface. Curiously, forward translation of the lens has been more commonly associated with the near accommodative response (cf., Coleman, 1970). Nevertheless, Morgan (1944) concluded that they had convinced themselves that accommodation is the result of reciprocal action and that negative accommodation was as much an entity as positive accommodation.

Although many researchers who favor the dual innervation position might agree with Morgan, not all would accept vascular changes as the sole source. Melton, et al. (1955) showed conclusively that there is SNS innervation of the ciliary muscle, but this is not necessarily to be viewed as an exclusive factor. In fact, Kuntz, Richins, and Casey (1946) supported Morgan's conclusion that vasoconstriction in the ciliary body is responsible for a part of the distant accommodation.

Further, Kuntz, et al. proposed a reflex innibition of the ciliary muscle through the adrenergic component of the short ciliaries.

Melton, et al. stimulated the short ciliaries and tne long ciliaries and measured ciliary muscle movements. Stimulation of SNS and PNS fibers produced responses that were always in opposite directions. Since this result was found in enucleated eyes, they reiterated Cogan's (1937) suggestion and implicated the radial fibers as the mechanism for increasing tension on the zonule and flattening the lens. Melton, et al. cite Meesman (1952) and Wolter (1953) as providing additional proof of dual innervation. Meesman apparently showed PNS induced contractions could be counteracted with sympathomimetic agents. Wolter demonstrated histologically tnat dual neural fiber groups supply the radial fibers of the ciliary muscle. He identified one of these fiber groups as sympathetic.

Pathways for sympathetic involvement are documented. For example, Monney, Morgan, Olmsted, and Wagman (1941) traced the sympathetic fibers from the first two thoracic nerves via the superior cervical ganglion to the long ciliary nerves and from there to the iris and ciliary body. Genis-Galvez (1957), in a carefully conducted histological study, determined that both SNS and PNS fibers were involved in ciliary muscle innervation. He also reported that the structure of the ciliary muscle appeared to be different from that observed in other smooth muscle.

Genis-Galvez was confident that the SNS fibers that he found did end in the ciliary body, but he cautioned that he believed their role to be limited. Further, in contradiction of Cogan's (1937) division of function based upon morphological indications, Genis-Galvez reported no morphological reason for supposing only one portion of the muscle to be under SNS control. He concluded that the antagonism of accommodation would not be based on separate innervations of the radial and circular portions but would be localized [sic] throughout the whole muscle.

The above conclusion implies not an active antagonism but rather an autonomic balance model of accommodation. This conclusion was echoed by Markham, Estes, and Blanks (1973) who in a slightly different context (utricular stimulation effects on accommodation) concluded that there is inhibition of the PNS influences passing from the Edinger-Westphal nucleus to the ciliary ganglion and then to the eye. Markham, et al. emphasized the complexity of the area referring to regulators of accommodation and the pupil within the the central nervous system.

Of course, the traditional alternative to this view (after Helmholtz) is that the resting position of accommodation is at optical infinity. It is this position that is consistent with a single innervation view of the ciliary muscle. A given level of accommodation would be the result of an antagonism between the parasympathetic input and the structural tension to return to this resting position. The precise mechanism for this structural tension has been variously described, but generally implicating tension from the supporting

structures of the eye transmitted through the supporting ligaments to pull the lens flat.

The difficulty with a single innervation system is the requirement for a constant input to maintain a resting position. It would be inefficient to provide a more or less constant input to maintain an intermediate position, although that alternative has not been empirically refuted. Westheimer and Blair (1973) have addressed this problem and described two parallel definitions of the resting positions. Since reduced stimulus fields result in accommodation of about 1.5 diopters (D) in man, there is definitive evidence for a resting position that is not optical infinity (the behavioral evidence will be reviewed later). Therefore, Westheimer and Blair proposed this condition to be representative of the physiological position of rest. Alternatively, there is the anatomical position of rest when the ocular muscles are devoid of nervous input, as in death.

Assuming an anatomical resting position exists, it is reasonable to question where this position would be. The excised lens and capsule tend to assume dimensions similar to those of maximum in vivo accommodation or beyond (Davson, 1972). In the absence of attachments, the lens of the cat assumes a theoretical refractive power of 12 D, but in place the empirical value is generally below 5 D. In addition, Fincham (cited in Davson, 1972) reported that the tendency of the decapsulated lens is to assume an unaccommodated shape. This implies a minor antagonism between the lens and the capsule, thereby serving to

complicate the issue further. Since the anatomical resting position should be a function not only of the lens and capsule but of the total system, manipulation of innervation to the total system is an important technique.

It is conceivable that the accommodative system could assume a position equal to near accommodation in the absence of nervous inputs. Cogan (1937) reported a personal observation that the monkey or human becomes accommodated for near immediately after death. He interpreted this to be the result of passing the sympathicotonic state of asphyxia. The absence of PNS input would allow the eye to become accommodated for distant vision, but the absence of SNS input might relieve tension on the supporting structure. This would allow the lens to perform as if it were excised, hence the maximal accommodation response.

In direct contradiction of Cogan, Westheimer and Blair (1973) supported the contention that the resting point (anatomical) is at optical infinity or the maximal radius of curvature of the lens. In darkness, monkeys exhibited alertness without visual stimulation with night myopia of 1.5 D of accommodation. During normal sleep (presumably under increased levels of PNS innervation) accommodation increased to 2.5-3.0 D. When the monkeys were awakened, accommodation immediately went to a far distance, followed by accurate accommodation to the ambient stimuli. Similarly inhalant anesthesia produced 3 D accommodation and the first stage of recovery was distant accommodation.

Under barbiturate anesthesia similar responses occurred, but as deeper stages were reached about .5 D of accommodation were lost. In two animals who were sacrificed, accommodation progressively went toward 0 D as death approached.

It appears that Westheimer and Blair have refuted Cogan's observation, but it would be instructive to determine whether the administration of overdoses of nembutal yields results representative of normal ciliary function. Accommodative measurements in cadavers have not been thoroughly investigated and the absence of this data creates problems for alleviating the apparent inconsistency between Cogan and Westheimer and Blair. Anatomically, it seems unlikely that Cogan is correct. Under maximum accommodation, it is well established that the tension has been removed from the lens by an active process and the lens tends to assume a shape like that when excised. Coleman (1970) noted that the effect of gravity increases the dioptric power of the eye when looking straight down and not when looking up (the back surface of the lens supported by the vitreous does not distend; therefore no increase in power is seen).

It is extremely difficult to draw definitive conclusions from any one source. Evidence from the anatomical and physiological work indicates that SNS inputs do affect the response of the ciliary muscle. A critical problem limiting the ability to summarize the literature elegantly is the multiplicity of species, manipulation methodologies, and measurement techniques. From the anatomical studies it is apparent

that sympathetic pathways exist. Interpretation of the histological findings is not always consistent. Generally, the role of the SNS in the ciliary muscle response is considered to be somewhat less important than the PNS.

A frequently cited study supporting the relative unimportance of the SNS in accommodation for distant vision was conducted by Tornqvist (1967) using cynomolgus monkeys (Macaca irus). Tornqvist concluded that the effect of sympathetic stimulation was small and developed and vanished much more slowly than that of the PNS; therefore, its importance remained questionable. Two points vitiate this argument: (1) stimulation was carried out against a background of parasympathetic activity, yet it still took increased accommodative response 1-2 sec to develop following oculomotor stimulation, and (2) the animals were anesthetized (pentobarbital, 30 mg/kg bodyweight). Westheimer and Blair (1973) subsequently demonstrated an increase in dioptric power under both inhalant anesthesia and nembutal. This latter effect presumably explains Tornqvist's (1964) finding that, under similar conditions, the monkeys were myopic prior to administration of the experimental treatment.

The work of Tornqvist (1966; 1967), although superficially a model of good experimental control, actually may have been biased against the likelihood of finding a SNS effect, given the many and varied PNS inputs present. Moreover, the relatively long response time for increased accommodation exceeds the normal movement time for environmental



stimuli. This suggests the possibility of minor anesthesia effects on response times in general (cf., Levett & Karras, 1977). The possibility of species differences should not be overlooked. Tornqvist (1967) noted that Olmsted (1944) had demonstrated a relatively large SNS effect in lower animals. As to a plausible mechanism, Tornqvist suggested that the lower animals may have an excitatory alpha-adrenergic innervation while the inhibitory beta-adrenergic mechanism found in other animals is relatively less effective.

Careful selection of experimental findings could allow one to support more fully the effectiveness of SNS innervation. For example, van Alphen, Robinette, and Macri (1962) used strain gauges to measure the effects of various drugs on excised strips of ciliary muscle. Both sympathetic and parasympathetic stimulants caused contraction in the excised strips, seemingly indicating antagonistic processes. There were, however, species differences and even within species different concentrations occasionally evoked opposite reactions.

van Alphen, et al. (1962) proposed that quantitative differences in interspecies responses reflect different force requirements for accommodation. They noted that not only are the lenses of different size, but ciliary muscles differ in structure and shape. The monkey's ciliary muscle-lens structure being much more conducive to accommodation. If SNS inputs do effect accommodation, van Alphen et al. saw no reason to assume that such innervation pertains exclusively to any of the three "divisions" (their quotation marks) of the ciliary

muscle. This position appears tenable, since sections taken in two different directions responded similarly.

The basic anatomical issue is still unresolved. Recently, Farnsworth and Burke (1977) used high resolution electron microscopy with methods of dissection allowing observation of the lens, ciliary body, and zonular system as seen in the intact eye. Their procedures avoided the difficulties attendant on fixing and drying procedures. They reported zonular architecture in the Rhesus monkey that differs substantially from that reported for other primates, including man. Although they acknowledged the possibility of interspecies differences, they suggested that the specimen preparation and the mode of observation were more likely responsible. In part, they concluded that "... tissue that responds to muscular contraction requires elements to produce the recall necessary to the relaxed state." Unfortunately, there is as yet no undisputed mechanism.

#### Anecdotal and Analogical Evidence

Perhaps one of the weakest (or least verifiable) sections of Cogan's (1937) argument for dual innervation theory is that concerned with cross-species comparison. Cogan noted that herbivores tend on the average to possess little positive accommodative power and carnivores only moderate development (e.g., 2-4 D in the dog or cat). However, in

the primates it is more highly developed, e.g., 10-15 D in apes and more in man. Cogan drew heavily on Collins' (1922) book on the evolution of the human eye. (Of course, it was barely half a century post-Darwin when Cogan wrote.)

Comparisons were drawn on the necessity for visual functioning at varying distances among these groups. It is apparently true that herbivorous animals are generally prey for the carnivorous, and distant (and panoramic) vision is adaptive. Likewise, carnivores only require near acuity for distances as close as their striking distance. Primate feeding habits (e.g., a diet of fruits and insects) demand a higher degree of visual acuity for small objects. Although this type of reasoning may arouse skepticism, the anatomical data comparing the ciliary muscles among these groups are apparently consistent.

Additional evidence on phylogenetic development is proposed by Duke-Elder and Wybar (1961) to help in understanding the morphology of the ciliary muscle. The parallel reasoning with Cogan is immediately apparent. The meridional (longitudinal) fibers are traceable to amphibians and become the ciliary muscle of reptiles (except snakes) and birds. In the lower mammals the muscle is lacking or vestigial. Only in the large-eyed placentals does it begin to resemble the triangular shape associated with human eyes. In ungulates, which have limited accommodation, only longitudinal fibers exist. Carnivores with relatively more active accommodation have the first traces of oblique fibers (a combination of the circular and radial fibers). Finally, it is

only in the primates that the tripartite complexity is manifested.

Another area with considerable bearing on the issue of an active antagonistic response for distant vision has been the measurement of accommodative reaction and movement times. This is an area with broad clinical and engineering implications. Clinically, evidence seems to show that age takes its toll both in amplitude (generally through outward movement of the near point) and speed of the accommodative response. Phillips, Shirachi, and Stark (1972) reported that Stark (then 45 years old) had notably longer latencies than two subjects aged 25 and 27. The generality of this anecdotal finding is probably true on the average, but wide intersubject variability limits the specificity of prediction for any one subject's response.

Latencies for accommodation to unpredictable stimuli are generally on the order of 300-400 ms. The actual value depends on several factors. The direction of the required response is important with near-to-far latency generally exceeding the far-to-near by about 20 ms (e.g., Phillips, et al., 1972). The magnitude of the stimulus change can be critical for speed and apparently accuracy of the direction of the accommodative response (cf., Troelstra, Zuber, Miller, and Stark, 1964). The nature of the stimulus input, for example, step changes versus sinusoidally modulated changes, can also influence the time course of responding (Charman and Tucker, 1977).

For predictable stimuli, Phillips, et al. (1972) have reported latencies to be much shorter than to unpredictable, but caution is in order. They also report many anticipations. As with other externally paced regularly occurring events, anticipations can create artificially short reaction times. In fact, they cite a previous experiment from the same laboratory in which the reaction time to a predictable stimulus was under 20 ms.

Reaction time to a target change is one way of looking at how the underlying physiology manifests itself. Because antagonistic processes have been proposed for accommodation, it should not be assumed that the reaction time for near-to-far will equal the reaction time for far-to-near. Reaction time is generally defined as the time between stimulus onset and the beginning of the response. Campbell and Westheimer (1959) report stimulus (sinusoidal) durations as short as 100 ms will evoke at least a partial response even when the stimulus has returned to its initial value prior to the movement initiation.

It could be anticipated that a given stimulus displacement would equally evoke responses from the current state if either near or far. However, at the nearer position relatively greater depth of focus exists (as a result of the attenuation in pupil diameter concomitant with the near accommodative response). The increased depth of focus could delay processing of the target position longer into the rise of the sine wave displacement, thereby accounting for the relatively longer reaction time for near-to-far target changes.

The data on movement time are not quite as prevalent (at least in English translation). Allen (1953a) reviewed much of the work up to that time and reported that researchers generally found the movement time near-to-far greater than far-to-near. The ratio of these times varied from 1.5/1 to 1.17/1. The latter value was determined by Kirchof (1950) who also reported a movement time of 426 ms for a 6.5 D movement. For a 2 D movement the averaged data plotted by Allen (1953b) appear to indicate a lower movement time, something on the order of 300-350 ms. Examination of the actual strips of optometer output provided by Phillips, et al. (1972) provides evidence for extreme variability in duration of responses to the signal (unpredictable in both amplitude and direction).

In a slightly different context, Levett and Karras (1977) measured both reaction time and movement time to shift of 2 D in the stimulus. Movement time for the three subjects ranged from 500-610 ms with essentially no differences for response direction. An additional manipulation in their experiment involved ingestion of graded doses of ethyl alcohol. There were general increases in movement time with increases in blood-alcohol levels. The three subjects were not affected equally, with one subject showing the greater effect on positive accommodation while another showed the greater on distant. The third demonstrated no differential effect.

The relationship between movement time, reaction time, and change in stimulus position does not in any sense conclusively prove there is

sympathetic as well as parasympathetic input. It might be expected, however, that a system dependent on only one innervation should show differences in movement time to stimulus changes in opposite directions. The most carefully controlled recent study does not support this conclusion, although previous evidence was suggestive of longer far accommodation movement times. Theoretically, longer movement time in far accommodation could be consistent with a single innervation system. The parasympathetic neurotransmitter (acetylcholine) has a finite decay time; therefore, the flattening of the lens should follow a time course related to that decay. Although this has not been experimentally verified, Cogan (1937) argued that the fact that any group of individuals (cf., Robertson, 1935) have shorter distant accommodation times provides evidence against such a possibility and convinced him that a single innervation theory was untenable.

It is not at all difficult to summarize the majority of the evidence in this section. Clearly, there is conclusive evidence for an intermediate resting position, thereby implying some mechanism for maintenance of this position. Schober (1954) has pointed out that the distance from 0.5 to 2.0 m is probably the most used visual range for human endeavor. It is less frequent that vision is required for other distances. The inherent adaptive advantages are self-evident. By itself the anecdotal and analogical evidence does not form an unbiased sample of opinions. Most of the studies cited suggest a dual innervation system as the functional mediator of the intermediate resting position.

Despite the questionable scientific basis for much of the evidence reviewed and its overall inconclusiveness, the accommodative mechanism would be unique among physiological systems if it were solely innervated by the parasympathetic branch of the autonomic nervous system. (Of course, the sweat glands receive sole SNS innervation, albeit with acetylcholine as the neurotransmitter.) As Toates (1972) argued, this places the onus on those who would deny dual innervation. Nevertheless, one's a priori beliefs may not be shaken by this evidence, nor should they be overly fortified.

#### The Dark Focus and the Anomalous Myopias

An important question has been the state of accommodation in the absence of external visual stimulation. Although most commonly used refractive techniques are impractical for measuring accommodation under conditions of darkness, the development of the laser optometer (Hennessey & Leibowitz, 1972; Leibowitz & Hennessey, 1975) and the infrared rangefinding optometer (Cornsweet & Crane, 1970) has made such measurements a simple matter. Moreover, the laser technique has been demonstrated to be effective without interfering with the magnitude of accommodation being measured (Hennessey & Leibowitz, 1970; Leibowitz & Owens, 1978), as is the invisible infrared pattern of the rangefinder optometer. Leibowitz and Owens (1975a; 1978) report that the mean value of accommodation under conditions of darkness is closely related to that



found under what may be called the anomalous myopias.

A puzzling and persistent problem in physiological optics has been the manifestation of inappropriate accommodation. The basic findings have been known for nearly two centuries, if not longer. In 1789, Lord Maskelyne, the royal astronomer, reported that the use of a negative lens facilitated his night observation (Levene, 1965) and more recently Rayleigh (1883) noted that he was distinctly myopic in a darkened room. This has become known as "night myopia." The phenomenon of "empty field myopia" (or "space myopia") has been discussed in detail by Whiteside (1957) with particular reference to high altitude flight (resulting in a stimulus-free external field or Ganzfeld). Also, when looking through microscopes, observers typically exhibit unnecessary increases in accommodation referred to as "instrument myopia" (Schober, Denler, & Kassel, 1970). These three situation-specific ametropias are referred to as the anomalous myopias (Leibowitz & Owens, 1975a).

#### The Dark Focus.

The laser optometer is particularly effective for investigating the focus assumed by the eye in the absence of light stimulation (the dark focus). Leibowitz and Owens (1975a) collected accommodative responses in the dark from 124 college students age 17 to 26 years (median = 18.9 years) and found that the mean dark focus value was approximately 1.7 D, corresponding to a focal distance of 59 cm. All observers had at least 20/25 near and far acuity. Those observers requiring optical

corrections were them during both the screening and determination of the dark focus.

In their sample only four observers had a dark focus of 0.5 D or less. To be consistent with the classical view, it would be expected that the majority would have had responses in darkness corresponding to optical infinity. Leibowitz and Owens also reported marked variability among their sample. The distribution is approximately normally distributed with a standard deviation of 0.72 D and a range of 4 D. Although this variability had not been suggested previously for the dark focus, others working on the topic of night myopia have hinted at such interobserver variability (e.g., Mellerio, 1966).

The empirical validity of the variability of the dark focus appears to be quite robust. Leibowitz and Owens (1973) replicated the essential findings of their earlier study with 220 college students who had a mean measured dark focus of 1.5 D. In 1975, Leibowitz and Owens had indicated the lack of an independent check on the adequacy of correction. They also report these corrections could affect the variability or magnitude of the mean dark focus. Of course, this is straightforward; the value of the individual's correction is added if negative or subtracted if positive from the dioptric value of the dark focus for that individual to determine his uncorrected resting state.

Recently, Benel and Benel (Note 1) collected dark focus responses from 85 randomly selected college students. Due to the particular

arrangement of the laser optometer, only individuals with a dark focus of less than 4.2 D could be measured. Thus, only those without contact lens corrections who had a dark focus of less than 4.2 D were retained for analysis. The distribution for these dark focus responses was negatively skewed with a mean of 2.71 D and a median of 3.0 D. The major difference between this and previous studies is the use of observers without their corrections. When corrected the mean for the entire distribution dropped to 2.56 D, although the distribution remained skewed. The residual mean difference between this and the previous findings is not easily resolved, but others have reported similarly near dark focus responses (e.g., Miller, 1978).

The weight of evidence indicates that in darkness the average eye assumes a position other than optical infinity. The precise accommodative position for an individual's eye is not easily predicted. Generally those with lowered distant acuity have nearer resting positions, but many with near resting positions have excellent distant acuity (Benel & Benel, Note 1). Wide individual differences appear to exist in lability of the accommodative response as well as its resting position.

### Night Myopia.

Although a relatively large literature on night myopia exists, much of the early work was equivocal. After reviewing the literature on ocular refraction at low luminance levels, Mellerio (1966) indicated that no more than 0.4 D of accommodation could be attributed to chromatic aberration. Yet, many argued that the residual portion could be due to spherical aberration (e.g., Koomen, Scolnick, & Tousey, 1951). However, earlier work in 1947 by Ivanoff (cited by Mellerio) had shown the spherical aberration of most eyes is strongly undercorrected when accommodation is for distant vision, but is overcorrected at about 4 D of accommodation; somewhere in between, usually at 1.5 D, the eye is aplanatic. Furthermore, night myopia may be shown to depend upon accommodation because instillation of homatropine reduces the myopia significantly (Otero & Duran, 1942).

Wald and Griffin (1947) provided further evidence for an accommodative cause of night myopia and concluded that the resultant variations in ocular behavior are caused by involuntary fluctuations of accommodation. They also noted that the average eye is fairly well corrected for spherical aberration. The reported range of values for night myopia is quite large with some observers exhibiting hyperopic shifts. It is presumably these large individual differences (and possibly some residual variance from the use of different techniques) that led to the disparity among results. The ensuing journal battle between Koomen, et al. and Otero and his colleagues was quite possibly

due to interobserver variability with only three and six observers respectively.

Several causes for night myopia have been proposed. Ivanoff (and originally Otero) had suggested that accommodation occurred to make the eye aplanatic. Some increase in accommodation would improve the retinal images in the extrafoveal regions which are distorted by spherical aberration. The second proposed cause and still most widely regarded was prevalent in the German research of the late 1940's and early 1950's (e.g., Schober, 1954). Namely, the rest point of accommodation in the absence of retinal images is responsible for night myopia. Since convergence may also occur in dim light, it could also be argued that night myopia is only convergence-induced accommodation. Furthermore, for a given observer any or all factors might be responsible.

The applicability of the first and third of the above proposed causes is questionable. In the first, viewing through small apertures will significantly reduce spherical aberration, but myopia will remain (Hennessy, Iida, Shiina, & Leibowitz, 1976). The third could be invoked plausibly as an explanation of all three anomalous myopias. However, Luckiesh and Moss (1940) had shown in the absence of convergence, myopia still occurs. Fincham (1962) demonstrated that the presence of retinal images in dim light did indeed stimulate fusional convergence, but in complete darkness there was no relationship between convergence and accommodation. In fact, Fincham pointedly stated that there was a distinct excess of accommodation. In addition, convergence changes only

bring about slight accommodation changes (Westheimer, 1966a). By far the most parsimonious explanation is that the night myopia is a reflection of the passive return of accommodation to its neutral, intermediate posture.

#### Empty Field Myopia

This is also known as space or sky myopia and is manifested when viewing an unstructured field (Ganzfeld) such as a clear sky, or during a snow storm or fog. This phenomenon is most clearly exemplified by Whiteside's (1957, p. 67) description of air-to-air search above the clouds:

...the direction from which it would appear was known. In spite of this help, when the target aircraft ~~was~~ [ital. his] seen it was almost invariably detected clearly and suddenly and was much nearer than would have been expected.... the impression of the difficulty in focusing was so strong as to give rise to a sensation of disorientation such as is sometimes experienced when one is in total darkness.

Whiteside surmized that accurate focusing to optical infinity would be possible only if the classical view (the emmetropic eye in its relaxed state is focused for infinity) were correct. Because no detail was available to be resolved, this would be a test for relaxed accommodation.

To examine the actual state of accommodation, Whiteside constructed a test pattern of dots so small as to be visible only when the eye was sharply focused. The pattern was brought toward the observer's eyes and the dots were not visible until they had reached the plane to which the observer was focused. The field appeared to remain empty until the dots were recognized. Unstimulated accommodation never equaled optical infinity but constantly fluctuated around a level of 0.5 - 2.0 D. More objectively, a Purkinje image photography technique verified these findings. The emmetrope was apparently unable to focus to optical infinity unless resolvable details were present at that distance. The similarity between this myopia and the previously well-known night myopia was duly noted.

Subsequently, Whiteside investigated the effects of removal of a target from the observer far point and from a near point. It was hypothesized that the maintenance of accommodation at a near point would be possible through the loose linkage between convergence and accommodation. The variable of interest was the time to return the resting level that had been seen in the first study. Observers attempted to "relax" accommodation as rapidly as possible to optical infinity from the near point or to maintain accommodation at the far point.

When the far stimulus was removed, accommodation increased involuntarily until it reached a level between 0.5 and 1.0 D. It was not possible to remain focused at optical infinity. It was possible

through convergence to increase accommodation voluntarily. Generally the time delay to reach the resting level was 60 sec in each direction, although the amount of fluctuation made it difficult to give precise values.

Whiteside concluded that the empty visual field considerably reduced the likelihood of accurately focusing at optical infinity. This difficulty was compounded by the probability that a conscious effort to accommodate for distance can result in focusing more closely to the intermediate resting position. Whiteside reported that under the empty field conditions, pilots engaged in air-to-air search often discovered that they had focused spots on their own aircraft canopy and not distant aircraft. This inherent bias to accommodate to a target at or near some intermediate distance rather than a more distant target has become known as the Mandelbaum Effect and will be covered under that heading.

#### Instrument Myopia

In contrast to the previous myopias, instrument myopia occurs during observation of targets of high contrast and rich detail. Hennessy (1975) provided a thorough review of the literature and reported the apparent lack of relationship between the change of the visual stimulus and the accommodative response during observation through an optical instrument. Luminance, magnification, wave length, and visual angle of the field have all been manipulated through a wide range with little effect on the magnitude of instrument myopia.



Although experience seems to ameliorate the myopia, it is still substantial. Other proposed causes include the suggestion that perceived distance is responsible (Schober, Dehler, & Kassel, 1970).

Hennessey tested three plausible causes of instrument myopia; the influence of peripheral stimuli, the effect of perceived distance, and the resting state of accommodation. Although previous evidence had been presented against any peripheral influence on accommodation, Hennessey and Leibowitz (1971) had demonstrated such an effect. Instrument viewing provides a situation analogous to looking through a field stop. There is a bright central field with a sharply defined dark peripneral surround. Schober, et al. hypothesized that apparent nearness of the magnified image may influence accommodation and result in the myopic response. Alternatively, in the absence of a requirement to accommodate there is the tendency for the eye to assume an intermediate position, the resting state.

Hennessey found that objects in the near-peripneral field can influence accommodation. This finding extended the previous work on the influence of a peripheral surround by demonstrating that the surround may even decrease accommodation when it is behind the fixation target. The peripheral stimulus did not, however, produce changes in accommodation large enough to account for instrument myopia. Despite producing changes in perceived distance by varying the relative size of a familiar object, no reliable changes in accommodation were measured. The mean refractive state while viewing a square-wave target through the

microscope was 1.91 D. This value is similar to others reported in the literature.

A comparison of the above data with observers' responses in the dark indicated a close correspondence ( $r = .78$ ). Hennessy concluded that instrument myopia and the dark focus are manifestations of the same phenomenon, the resting state of accommodation. In a replication, Leibowitz and Owens (1975) report a similar results. Once again, there was close correspondence between the refractive readings in the dark and when observation was through optical instruments ( $r = .68$ ).

The relatively small exit pupil diameters of microscopes (2.0 mm or smaller) increase the depth of focus of the eye and eliminate the need to accommodate. Without this requirement, the eye may passively return to its resting position with no loss of acuity. Leibowitz, Hennessy, and Owens (1975) also describe this as allowing the observer to select a focus that is most comfortable and/or permits the clearest image. The resting position explanation does not eliminate other causes, but relegates them to a minor role.

In addition to the literature on the dark focus and anomalous myopias, it has also been demonstrated that observation through small apertures will cause accommodation to assume an intermediate state generally in the range of 1 - 2 D (Hennessy, Iida, Shiina, & Leibowitz, 1975; Roscoe, Randle, & Pettit, 1976). Leibowitz, et al. (1975) state their basic strategy has been to ask, experimentally, where the eye

accommodates when (1) the need to accommodate is eliminated and (2) the stimulus for accommodation is degraded.

The evidence from this area is overwhelmingly in favor of an accommodative resting position that is nearer than optical infinity for the emmetropic observer. The situational ametropias could be considered anomalies, rejecting by fiat the possibility that they are a manifestation of an underlying intermediate balance point, and thereby maintain the classical view that the physiological resting position of accommodation is at optical infinity. Alternatively, we could accept the parsimonious explanation of Leibowitz, et al. that in the absence of an adequate stimulus there is merely a return to the intermediate resting state. Those who would maintain the classical view are faced with the considerable task of explaining this evidence within the context of the conventional textbook wisdom.

#### Summary

Cogan opened his 1937 review by stating:

The role of the sympathetic nervous system in accommodation has been variously assumed and denied, but its active participation seems necessary to explain certain clinical and experimental phenomena.... It would

appear that the sympathetic system tends to adapt the eye for relatively distant objects and as such opposes the parasympathetic system, which tends to adapt the eye for relatively near objects.

The above statement still characterizes the conclusion that can be drawn from the evidence. Likewise, as Cogan stated (p. 739), "The mechanism whereby the sympathetic system effects this distance adjustment is not obvious."

This latter statement concerning the mechanism assumes an intermediate position of rest for the lens and ciliary muscle. The preceding experimental and clinical phenomena, e.g., anomalous myopias and dark focus, provide sufficient evidence to refute the validity of a physiological resting position at optical infinity. No matter how intuitively appealing a resting position at 0 D might be (as Morgan noted in 1957, what can represent less activity than zero), many experiments have now proved otherwise.

A proper test for a "resting" state can only be conducted when the lowest level of ambient stimulation is present. Morgan (1957) proposes two possible conditions in which visual stimuli are reduced to the minimum--in complete darkness and in a luminous but completely empty visual field. The circle is closed and we are drawn to the ineluctable conclusion that the average eye when presented with no patterned stimulation assumes a position other than optical infinity. The exact

value that the eye assumes varies widely among observers, but can be roughly estimated to be at arm's length.

Leibowitz and Owens (1975a) noted that researchers have reported the intermediate state to involve no accommodative effort. If this means no neuronal inputs, this does not appear feasible in view of our current anatomical knowledge. However, the idea of autonomic balance comes to mind as a mechanism, as it implies no excess inputs in either the near or far directions. While antagonistic peripheral systems are unnecessary for an autonomic balance position, they are not excluded and they are consistent with much current evidence (e.g., Genis-Galvez, 1957; Markham, et al., 1973). No conscious effort is implied in maintaining this intermediate focus, and increases in activity of either branch of the autonomic system would yield opposite reactions. In the absence of neuronal input (death) the system is allowed to approach its anatomical resting position.

Perhaps this position would be acceptable even to such a severe critic of Cogan as Luedde. After all it was Luedde (in the discussion of Cogan, 1937) who had suggested that the drug effects reported by Cogan probably indicated inhibition of the parasympathetic fibers rather than primary stimulation of the sympathetic fibers. Indeed many effects of sympathetic stimulation could be interpreted as evidence supporting this autonomic balance position in the absence of demonstrated separate functioning of portions of the ciliary muscle. Unfortunately, Cogan (1937) thought that evidence corroborating inhibition, and hence the

autonomic balance position as the entire vis a tergo in distance accommodation, was lacking. Much research since then has indicated the necessary components can be identified, but as Morgan (1957) concluded, the action of the sympathetic, whether vascular, muscular, or both, remained unestablished.

To return to the intact organism, remaining fully cognizant of an empirically identified intermediate resting position, it has not been possible to date, and it is unlikely that we will ever identify any one mechanism as being solely responsible for active distant accommodation. It is possible that all mechanisms could be responsible, but to a different degree between species or even between individuals within a species. Markham, et al. (1973) proposed a combination of parasympathetic inhibition and sympathetic facilitation in distant accommodation. This proposal thereby encompasses the possible mechanisms and seems intuitively reasonable, although it admittedly begs the question of exact mechanisms and proportions of accountability.

## THE ACCURACY OF STEADY-STATE ACCOMMODATION

Steady-state accommodation refers to the absolute level of accommodation under a given stimulus condition contrasted with dynamic accommodation referring to directional shifts (after Owens, 1976). Generally, it has been assumed that, in the absence of refractive error, accommodation responds accurately throughout its range. However, many researchers (e.g., Morgan, 1944), who have explicitly measured the actual accommodative state, have found that accommodation tends to be insufficient for near targets and excessive for far targets. This appears consistent with the notion of an intermediate resting position. Accommodation is predicted to be most accurate for targets at a distance corresponding to the resting position, while accommodative lead (relative myopia) will occur for more distant targets and accommodative lag (relative hyperopia) for nearer.

### Stimulus Parameters

Campbell (1954a; b) was among the first to investigate the effects of varying the spatial characteristics of the visual image as determinants for the accommodative response. In his first experiment he found that the luminance threshold for an accommodative response increased when target size decreased. In the second experiment,

luminance was held constant at a photopic level and he found that the smaller acuity targets elicited a more accurate response than the larger. He also found that subphotopic luminance eliminated the accommodative response, leading him to conclude that foveal cone receptors were the critical elements for the accommodative system.

Although Cambell's proposal was intuitively appealing and appeared consistent with existing evidence, more recent work raises questions concerning the validity of his hypothesis. The possible influence of the peripheral visual field had been disregarded presumably because of the poor image quality, but the phenomenon of instrument myopia suggested involvement of the peripheral visual field. When Hennessy and Leibowitz (1971) pitted strong peripheral cues against a relatively weak foveal stimulus, observers accommodated to changes in the distance to the peripheral surround while viewing a central target at a fixed distance. This implies that the visual context surrounding a somewhat degraded fixated object can affect the focal state.

In a subsequent experiment, Hennessy (1975) manipulated the effectiveness of peripheral stimuli by employing both checkered and black annular surrounds. In this experiment, the checkered surround had a marked effect drawing accommodation toward its position. The homogenous dark surround had no such effect. Although the influence of peripheral stimulation on accommodation does not fully explain instrument myopia it may be of considerable significance in various contexts. They also showed that accommodation may be decreased by a relatively more distant



surround. Thus, Fincham's (1951) opinion that only fixated objects can stimulate accommodation appears incorrect. Within many experimental contexts in which reduction screens and other devices that reduce peripheral cues have been used, investigators may have assumed certain accommodative states that were not verified and, in fact, may not have been verifiable. A complete reexamination of those experiments is beyond the scope of the present review, but it appears that such assumed conditions are suspect.

It has been argued that resolvable detail is the critical element necessary for accurate accommodation (e.g., Heath, 1956a; b). Heath (1956b) measured accommodation to a Snellen chart over a range of optical distances. When the view to a target was systematically degraded, either by ground glass at the chart or by lacquered lenses at the observer, both acuity and accommodative accuracy were reduced. The lead and lag of accommodation were increased, and observers approached a fixed intermediate refractive state similar to that which the observers in Johnson's (1976) study showed under luminance reduction. Fincham (1951) and Smithline (1974) both observed no accommodative changes to changes in the optical distance of a severely blurred target.

Furthermore, a small bright fixation point in a dark surround is not an adequate stimulus for accommodation (Owens & Leibowitz, 1975). Similarly, Benel and Benel (1979) measured accommodation to 0.67-degree transilluminated discs at various distances. Despite the fact that the discs provided photopic luminance, accommodation was notably inaccurate

to discs presented at other than the dark-focus distance. The results paralleled the findings of Heath (1956b) and Johnson (1976), namely, the lead and lag of accommodation approached a fixed refractive state highly correlated with the dark focus.

More recently, researchers applying Fourier Analysis to the visual system provided a technique that can lead to resolution of these inconsistencies. The spatial distribution of light in the visual image can be analyzed into component sine waves. In the typical experiment, the observer's contrast threshold for sinusoidal gratings of various spatial frequencies is measured. Contrast sensitivity is plotted as a function of the spatial frequencies of the stimuli. The sensitivity function (CSF) peaks between 0.5 and 14 cycles per degree (c/d). Above 20 and below 0.1 c/d minimal sensitivity is obtained (Cornsweet, 1970). Although this application involves some major assumptions and perhaps may be an overgeneralization, it does provide a useful measure of visual resolution.

Owens (1976) has hypothesized that any target containing spatial frequencies that fall outside the observer's optimal sensitivity range should not be an effective stimulus for accommodation. Low frequency targets, such as degraded acuity targets or at the extreme the Ganzfeld, would be poor accommodative stimuli. Similarly, high-frequency targets like the fixation point would also be inadequate.

Charman and Tucker (1977) measured accommodation to sinusoidal grating targets as a function of the spatial frequency of the grating and its optical distance. For targets presented at optical distances calling for 1, 2, and 3 D of accommodation, the response curves for an observer with an empty-field focus of 2.9 D all had similar functions. With very low spatial frequencies, responses approached the empty-field response. At 5 c/d the responses approximated accurate accommodation across distances. When the observer viewed a target at the inward limit of his accommodative range, accommodation to the high-frequency targets ( $\geq 30$  c/d) was impossible unless a lower frequency were available to aid him in locating the region of a correct response. Charman and Tucker suggested that accurate accommodation at the limits of the accommodative range is not achievable with single-frequency targets.

There was an apparent tendency for observers viewing complex targets (e.g., Snellen letters) to depend on low-frequency components to guide the accommodative response to its final level. Charman and Tucker (1978) suggested that the ambiguity of focus present with sinusoidal grating targets can be greatly attenuated when observers view such wideband targets. Accordingly, only when the eye has already moved closer toward the correct focus do the high frequency components play their role in producing a more accurate steady-state response.

The influence of illumination on the steady-state accommodative response is most obvious in the case of night myopia, wherein lowered target luminance results in an accommodative response nearly identical

to the dark focus (Leibowitz & Owens, 1975a; 1978). Leibowitz and Owens (1975b) varied luminance of the same scene with filters to produce daylight, dusk, and moonlight conditions. Consistent with their other findings, the accommodative response most resembled the dark focus when the luminance was equal to moonlight and least for the daylight. Interestingly, in no case did accommodation equal 0 D nominally required by the scene being viewed. Once again the lead of accommodation was seen.

Johnson (1976) varied luminance and stimulus distance while measuring accommodation and visual resolution. All observers displayed the lead and lag of accommodation, but errors were relatively small at the highest luminance. With the lowest luminance (0.0017 ftL) observers tended to assume a fixed focus equal to the dark focus. Not surprisingly, visual resolution was at a maximum when accommodation and target distance were most closely matched. This implies again that accommodation and visual resolution will be most accurate at the dark focus and that both will show a decline when target distances either exceed or are within that distance.

#### Viewing through Small Apertures

The requirement for the eye to accommodate can be greatly reduced if the depth of focus is sufficiently increased. Viewing through small

apertures can provide in-focus images over a wide range of accommodative levels. Although researchers investigating instrument myopia typically use approximately 2.0 mm exit pupils (e.g., Hennessy, 1975; Leibowitz & Owens 1975a; 1978), some researchers have employed much smaller pupils for various purposes. Unfortunately, many of these researchers did not report accommodation, but Hennessy, et al. (1975) found that with pupil sizes decreasing from 3.0 mm down to 0.5 mm accommodation tended to assume a fixed value regardless of target distance. Generally, the decrease in accuracy was monotonically related to the decrease in pupil size.

Roscoe and Benel (1978) report the effects of the insertion of a small aperture upon accommodation while viewing targets. The use of an infrared optometer (Cornsweet and Crane, 1970) provided the opportunity to follow the time course of an essentially open-loop accommodative response. Although there were individual differences in resting level and in the rapidity with which the response occurred, there was a general lapse toward the resting state. These shifts occurred while the observer continued to view the same target pre- and post-insertion of the aperture. Occasionally observers showed marked fluctuations of accommodation without any reported blurring of the target.

### Summary

As a minimum, two conditions appear necessary but perhaps not sufficient for accurate accommodation: (1) adequate textural cues and/or perspective cues for distance and (2) a requirement to attend to the stimulus (e.g., to make a discrimination). Perhaps the former are describable in terms of their frequency components. Although a strict Fourier analysis appears inadequate, it may apply in monocular settings with single, foveally presented targets where textural cues alone are available. The requirement to attend to the stimulus is often overlooked. The implicit assumption that a target reflexively induces accurate accommodation for its optical distance is suspect.

In a recent review (Hochberg, 1971), the role of accommodation as a cue for distance and size was examined. Interestingly, the proposed test for the influence of accommodation as a depth or distance cue required that all other cues of distance be eliminated. Similarly, a presumably "fair" test of the role of accommodation in size judgments would demand the reduction experiment setting. Yet, this requirement has been demonstrated to eliminate one of the features essential for an accommodative response to occur. Under reduced conditions, assumed changes in accommodation may be merely figments of the experimenter's imagination and may be incapable of accurate independent manipulation.

Two possible avenues exist to eliminate the circularity inherent within this cue/accommodation dilemma. One avenue is to train observers

to achieve volitional control over accommodation. In studies of dynamic accommodation, some observers have developed the ability to identify and use alternate sources of information to maintain directionally accurate responses (Westheimer 1966a; Morgan, 1968). More explicitly, observers can be trained to use non-visual signals to direct changes in accommodation (Cornsweet & Crane, 1973; Randle, 1975; Malmstrom & Randle, 1976). Unfortunately, no one has demonstrated an ability to achieve a given steady-state accommodative response on demand. Owens (1976) suggested that steady-state accommodation is more stimulus bound than dynamic accommodation. The second possibility involves the establishment of a reasonably accurate steady-state response under one setting and a procedure for reliably shifting the accommodative state. In the following section a phenomenon is described that encompasses these two conditions.

## THE MANDELBAUM EFFECT

Quite frequently observation of relatively more distant objects occurs through an interposed surface, e.g., a pane of glass or a window screen. Under these circumstances the eye has the possibility of focusing either the interposed surface or the target object. Mandelbaum (1960) was apparently the first to document the circumstances under which the eye would focus the interposed texture rather than the target object. The initial finding arose from the serendipitous discovery of an inability to focus the distant skyline while observing through a mesh window screen. Despite increased subjective effort to view the distant skyline, Mandelbaum was unable to bring it into focus. It occurred to him that he was, in fact, accommodating to the screen.

Mandelbaum's Experiment

After amusing himself and other tolerant individuals for many years, Mandelbaum was presented with an ideal circumstance in which to investigate the phenomenon more fully. The summer cottage that he had rented had the requisite screened porch and, fortuitously, a view of a sign saying "Private Beach" with letters subtending 6.3 min. He conducted an informal experiment in which he could easily demonstrate



that the letters of the sign became completely illegible when the observer was positioned a certain distance from the screen.

Individual differences in the critical distance were apparent among the 21 observers who participated. When the observers started at the screen and moved back, the onset of blurring ranged from 14 to 25 inches (6 to 10 cm). The region of maximum blur occurred between 1 and 2 m. At distances beyond 2.75 m the blurring had subsided entirely. Administration of a cycloplegic demonstrated the effect to be due to accommodation and in a control condition employing a mydriatic he eliminated pupillary changes as a causative agent.

Owens (1976) pointed out that the angular subtense of the screen in Mandelbaum's experiment would change as a function of distance, possibly influencing the interpretation. The possibility existed that the screen, when positioned at a critical distance, provided a more effective stimulus than the sign. On the other hand, its effectiveness might be due to the close correspondence between the screen distance and the resting position distance. Owens posited that focusing the screen under these circumstances required less accommodative "effort" than focusing the sign. Certainly, the individual differences inherent in the resting position were consistent with the finding of different critical distances by Mandelbaum.

### The Owens' Experiments

Owens (1976) tested the hypothesis that the "Mandelbaum effect" resulted from a correspondence between the interposed screen and the observer's resting accommodation. Owens presented a distance other than the dark focus, while, at the same time, another adequate stimulus was superposed at a distance equal to the dark focus. Both stimuli were presented in Maxwellian view thereby avoiding changes in image size with changes in optical distance. The apparatus was arranged so that stimuli could be presented simultaneously with no loss of contrast to either stimulus. The expectation was that accommodation would be drawn toward the stimulus presented at the dark focus distance.

After determining that the screen and target (3 x 3 matrix of Snellen Es) were of equal adequacy as accommodative stimuli, Owens placed the target at the observer's dark focus, 0 D, and 5 D and varied the placement of the screen from 0 through 5 D in 1 D increments. The results supported the hypothesis that the Mandelbaum effect was related to the correspondence between the screen and the observer's dark focus. This suggested that the eye would consistently focus the stimulus closer to the dark focus or resting position.

A second experiment was conducted in which observers were allowed to focus the "easier" of two targets presented in the same apparatus. The stimuli were always presented with an optical disparity of 2.0 D. Observers consistently focused the target optically nearer their dark

focus. If the stimuli were situated such that the dark focus fell between them, observers would fluctuate between the two targets when instructed to observe the clearer target passively. If required, observers could hold accommodation to either target with minimal effort.

### Summary

The evidence provided by Owens (1976; 1979) certainly adds to the support for a relaxed position of accommodation at other than the far point. If the relaxed position of the lens were at optical infinity, then in Owens' first experiment the screen would have been expected to exert no influence on accommodation to the more distant targets. In the second the more distant target would have been expected to be focused more easily under all combinations. As Owens concluded, the dark focus appears to represent a preferred state of accommodation influencing focusing behavior in the presence of adequate stimuli as well as the reduced cue situation.

In terms of mere acuity for objects viewed through interposed surfaces, the results are of obvious importance. A great many practical situations require the viewing of distant objects through interposed surfaces. Perhaps the most ubiquitous is automobile operation. Dirty or streaked windshields might represent a more effective accommodative stimulus than the distant pedestrian or road sign, particularly when the

driver has a dark focus near 1.5 D (taking the equivalent distance of .67 m to be representative of the distance from observer to windscreen). Also, water and snow on windscreens can present resolvable contours in addition to their already disruptive effect on acuity.

In aircraft operation with similar observer-to-windscreen distances the effect would be expected to be manifested and perhaps exacerbated by a reduction in visual foreground texture (cf., Iavecchia, Iavecchia, & Roscoe, 1978). Aircraft windscreens have been known to be particularly susceptible to scratching (being made of plastic compounds) and are often significantly distorted (e.g., Gomer & Eggleston, 1978). The effects of geometrical distortions aside, "rainbowing" and other optical defects could provide accommodative cues in otherwise clear windscreens.

The possibility of effects beyond acuity loss is suggested by the previously presented demonstration described by Hoffman. Certainly the accommodative shifts that occur under the Mandelbaum effect can be related analogously to the shifts occurring within the demonstration. The relationship of these former shifts to systematic changes in apparent size of objects viewed simultaneously has not been examined previously.

## SPATIAL CHARACTERISTICS OF THE STIMULI

Benel and Benel (1979) have suggested that, the further a stimulus is from an individual's resting position, the higher in stimulus value (as yet an unquantified variable) that object must be to elicit reasonably accurate accommodation. Owens (1976; Note 2) has proposed quantifying the effectiveness of a stimulus by optically varying the distance of the stimulus and simultaneously measuring accommodation. The slope of the regression of accommodation on stimulus presentation distance indexes the target's adequacy as an accommodative stimulus. Accordingly a slope of 1.0 would indicate veridical accommodation for the object distance and presumably the greatest adequacy as an accommodative stimulus. Typically slopes of less than 1.0 are found, reflecting the presence of accommodative lead and lag for more extreme presentation distances even when targets are of high contrast (e.g., Owens, 1976).

Although regression slopes are not often reported, visual inspection of reported data indicates slopes of less than 1.0 to be general. Heath (1956b) changed resolution values associated with Snellen letters either by interposing ground glass at the target or lacquered lenses at the observer and found that accommodative responses diminished in accuracy with diminishing resolution. Likewise, varying the contrast modulation and spatial frequency of sine waves can lead to similar results (Charman & Tucker, 1977; 1978). Lowered illumination has equivalent effects on accommodative accuracy (Johnson, 1975).

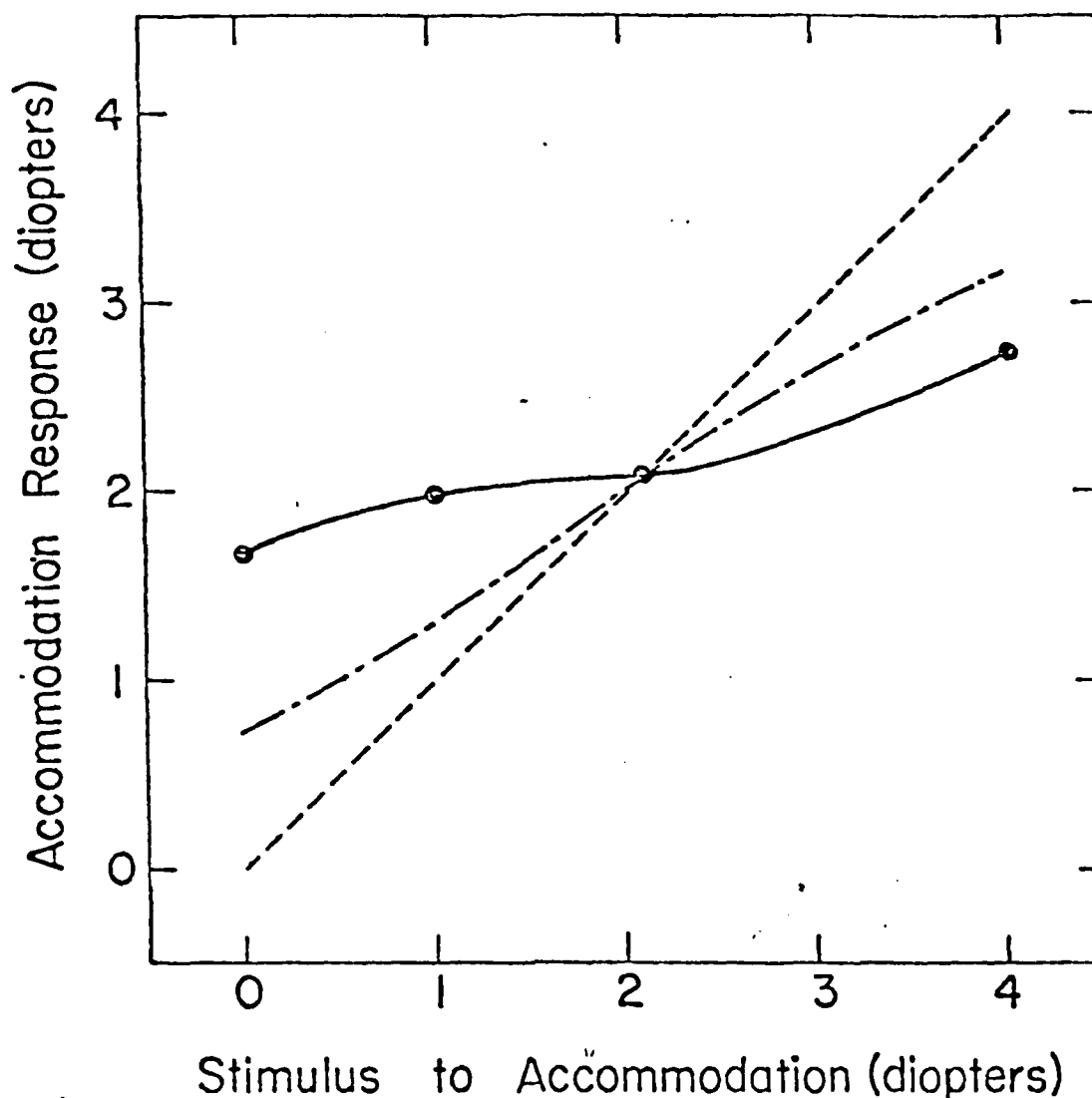


Figure 2. Loss of accommodative accuracy with decline in accommodative draw of stimuli. Crossover near the dark focus is typical.

Figure 2 illustrates the relationship between accommodative accuracy and stimulus parameters. The accurate accommodation line (steepest slope) represents the response function that would result if accommodation precisely matched the optical distance of stimulus presentation. The function labeled textured stimuli is generalized from data presented by many researchers and represents typical accommodation to well-defined, high-contrast targets, e.g., Snellen Letters. The

heavy dark line labelled untextured stimuli is derived from data presented by Benel and Benel (1979). In that study observers viewed transilluminated discs subtending 0.67 degree of visual angle at varying optical distances. Although these discs had well-defined outlines, accommodation was generally much less accurate than had been found with more complex targets.

The use of slopes as a measure of the accommodative value of a stimulus affords the opportunity to equate stimuli that would be difficult or impossible to compare in spatial characteristics. The variety of physical parameters that characterize stimuli presents the considerable task of selecting one or a set of descriptors. The application of slopes provides a common metric representing a response tendency and avoids the difficulties attendant on the selection of an arbitrary physical characteristic that may or may not be relevant.

Owens (1976; 1979) employed this technique to equate the stimuli that he used to investigate inappropriate involuntary accommodation in the presence of competing stimuli as a function of the individual's dark focus. The relevant stimuli were not only similar to each other in slope, but approached a slope of 1.0. Within that context and for the intended purpose, those stimuli were entirely appropriate. Under other circumstances, stimuli not only vary from one another but are also less likely to generate accurate accommodative responses across a wide range of presentation distances.

### Experiment I: A Functionally-based Metric

The primary purpose of this experiment was to determine the feasibility of the use of regression slopes to express accommodative stimulus value and to provide a set of stimuli to be used in the subsequent experiment. Stimuli that ranged from sharply imaged gratings to grossly blurred images of the same targets were presented at varying optical distances and the observers' accommodative responses measured. Although these stimuli could be described more objectively (e.g., Fourier analysis, density profiles of the resulting transparencies), this technique allowed stimuli to be ordered and quantified in terms of the generated accommodative response. Under actual viewing conditions the generated response may be more relevant than other metrics that may or may not relate to actual visual functioning (cf., Ochs, 1979).

Several critical issues bear on the determination of the usefulness of regression slopes as an index of accommodative adequacy of stimuli. The relationship between individual differences and the regression of accommodative responses on presentation distance is undefined. Owens (1976; Note 2) provided data from four observers that indicated interobserver variability existed at each target condition, but the trends across observers were similar. Namely, accommodative response slopes peaked at an intermediate spatial frequency for the sine wave stimuli and fell off toward the extremes. To be most useful, slopes must not be idiopathic with no meaning except for individual observers. If individual differences exist, the predictability of an individual's



response as a function of some personal characteristic, i.e., the dark focus, is crucially important.

Figure 3 indicates two possible relationships between response slopes and the resting position, a likely individual characteristic that may effect the relationship. The triangles represent the crossover point between accommodative lag and lead (generally thought to be equal to or correlated with the dark focus). In the upper graph, the generated functions indicate no interaction between slope and resting position. Therefore, these two measures would be uncorrelated, but intercepts and resting positions would be positively correlated. The lower graph represents the case in which both slopes (negatively) and intercepts (positively) are correlated with the resting position.

Another issue concerns the position of the crossover point. This has been referred to as the "fulcrum" for the accommodative stimulus-response relation (Johnson, 1975). The position for the fulcrum has been generally described as the dark focus. Yet, reliable differences between resting positions have been found (Benel & Benel, 1979) suggesting that the particular position for the fulcrum may not fall necessarily at the dark focus. For example, the empty field condition more nearly resembles the viewing conditions when the stimulus has not been resolved, i.e., an apparently uniformly illuminated stimulus field.

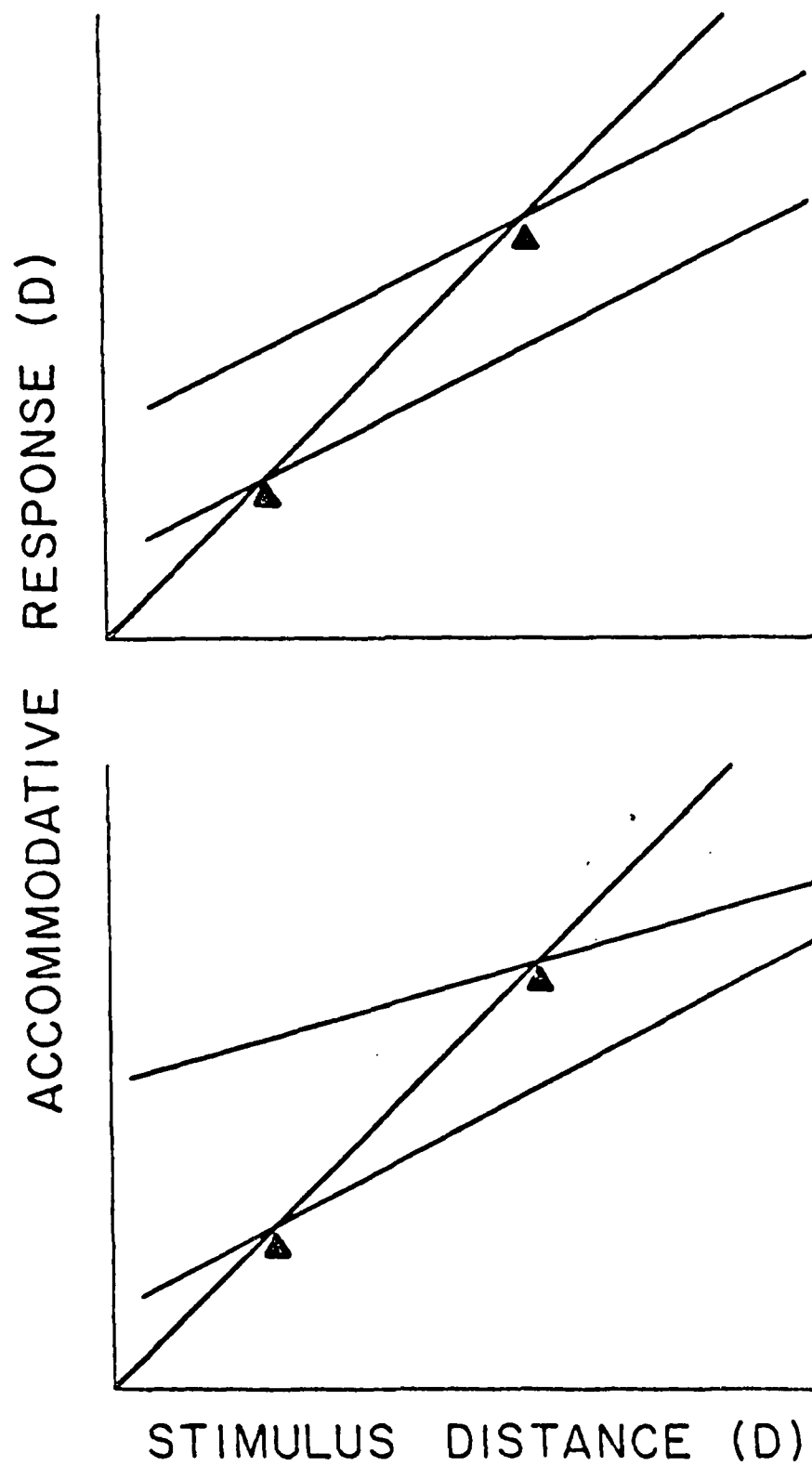


Figure 3. Two possible relations between the accommodative "fulcrum" and the slopes and intercepts of the regression of accommodation.

Accordingly, several resting measures were taken to ascertain the degree of relationship between each measure and the fulcrum position. Both a light and dark focus were measured with the visual field of the occluded eye matched for luminance (i.e., dark for the dark focus and light for the light focus) or mismatched. Matching luminance in the occluded eye may further explicate the reliable differences among resting measures. Generally, the dark focus has been measured in complete darkness, but Ganzfeld measures of the empty field provide a mismatch with the luminance in the occluded eye (e.g., Leibowitz and Owens, 1975). A useful byproduct of this manipulation was the opportunity for assessment of differences between these various measures and a short-term (within session) determination of their stability (test-retest reliability).

Therefore, this experiment was designed to determine the following:

- (a) Can slopes of the regression of accommodation on presentation distance be used to index the accommodative adequacy of stimuli?
- (b) Are slopes and resting measures independent, and if not independent, are there lawful relationships between them such that slopes can still be useful?
- (c) What is the relationship among resting position measures?
- (d) Which resting position measure (if they differ) is most representative of the accommodative fulcrum?
- (e) What are the short-term reliabilities of the resting measures?

## Method

Observers. Twenty-four volunteers between the ages of 13 and 30 years were selected to serve as observers. All observers were nominally emmetropic and had near and far visual acuities of at least 20/25 as measured by a Bausch and Lomb Modified Orthorater.

Stimuli. The screen stimulus prototype consisted of crossed rectilinear strands subtending 7.2 min visual angle (VA) separated by 15.3 min VA. The series of four screen stimuli was produced by successively defocusing the image. This was accomplished by placing high-contrast photographic positives (black lines on a clear background) at various distances from a matte diffusing surface. The non-blurred stimulus was produced by placing the transparency on the side of the matte material toward the observer (thereby maintaining luminance equivalent to the other conditions). The most defocused stimulus was produced to appear nearly uniformly gray when viewed at the plane of focus. Two intermediate stimuli were also produced.

The percent contrast associated with each stimulus (3, 15, 75, 95) was computed according to the following formula:  $\text{Contrast}(\%) = 100 (LB-LT)/LB$ . The background luminance (LB) was that measured for the light area and target luminance (LT) was that measured for the dark area. The stimuli were projected through a modification of the viewing system described below and luminance measures were then taken with the spot-meter also described below.

Apparatus. Stimuli were presented by means of a two-channel Maxwellian view optical system. Channels 1 and 2 were constructed in series so that no reduction in the contrast of either stimulus would occur and stimuli could be presented at independent optical distances. Figure 4 presents a schematic diagram of the apparatus. A Sawyer projector (model 500XM) with CWD projection bulb (120 V, 300 W) served as the light source. Lenses L1 and L2 formed a bright field on the opal glass diffusing screen (OG1). This source was masked by a field stop (FS1) to form an image 14 mm in diameter at the plane of the observer's entrance pupil.

Stimuli were positioned in the collimated portions of Channels 1 and 2 between lenses L3 and L4, and L5 and L6, respectively. Movement of the stimuli within each channel varied the optical distances independently. Lenses L3 through L6 are 180 mm focal length yielding a maximum dioptric power for each channel of 5.56 D and equal magnification within each channel. The diameter of the circular stimulus field subtended 12 deg VA. The size was limited by a field stop (FS2) placed at -5.56 D (beyond optical infinity). The field stop provided a severely out of focus edge image that would not act as an accommodative stimulus (Heath, 1956b; Smithline, 1974).

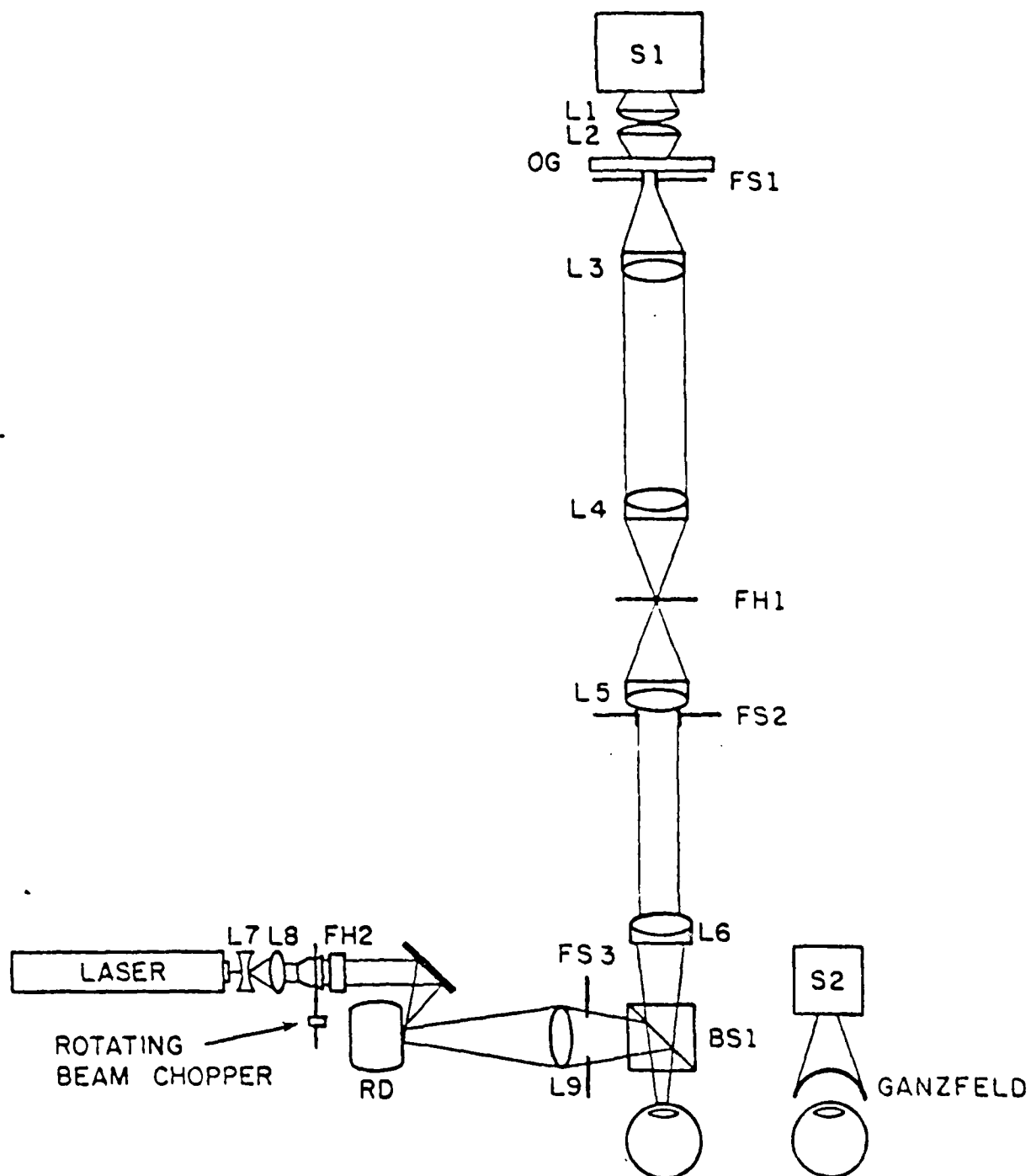


Figure 4. Schematic diagram of the Maxwellian viewing system and the accommodation measurement apparatus.

Luminance of the stimulus field was controlled by a variable transformer at the source. Light from an additional source (S2) illuminated a Ganzfeld visible to the observer's right eye. This luminance was matched to the Maxwellian view. The Ganzfeld was created by a half ping pong ball that was glued to an eye patch with a hole cut in it.

Accommodation was measured through a third channel consisting of a laser optometer similar to that described by Hennessy and Leibowitz (1972). The beam of a 2.0 mW He-Ne laser (Metrologic Model MC-650) is diverged (L7), collimated (L8), and then reflected by a mirror (M1) from the surface of a slowly rotating drum (RD). The resulting speckle pattern masked to subtend 10 deg VA was superposed on the observer's field of view by means of a beam splitter (BS1). The intensity of the speckle pattern was adjusted with crosspolarized filters (FH2) until only the brightest speckles remained visible. The exposure duration (0.5 sec out of 5.0 sec) was controlled by a rotating beam chopper.

The test pattern speckles indicate the observer's refractive state. If the observer is overaccommodated (relatively myopic) for the test pattern, the speckles appear to "flow" with the drum's rotation; if underaccommodated (relatively hyperopic), they appear to flow in a direction opposite the drum's rotation. When accommodation places the "plane of stationarity" (Charman, 1974) conjugate with the retina, the speckles appear stationary or merely swirling but do not "flow" in either direction. Bracketing movements are made with the drum until

the plane of stationarity is located.

According to the Badal principle, the insertion of a positive lens in the light path of the laser pattern one focal length from the observer's entrance pupil allows the plane of stationarity to be varied from nearly the dioptric power of the lens to beyond optical infinity with essentially no changes in the brightness or size of the test pattern (Ogle, 1971, p. 226). An additional correction (.32 D) for the monochromatic light of the He-Ne laser (632.8 nm) must be added. The resulting optical distance of accommodation is read from a properly constructed scale.

Luminance measures were obtained with a Spectra Brightness Spotmeter Model (UB-1/4). The Maxwellian view was measured using the method of apparent luminance matching. A variable source was set to appear equal in brightness to the Maxwellian view, and the luminance of that source was measured with the spotmeter. The luminance of the Maxwellian view was determined to be 1.5 log ftL. All other luminance measures were taken directly and where appropriate matched to the Maxwellian view. A dental impression bite-board adjustable in X, Y, and Z planes held the observer's eye in proper position. Screens of black construction board prevented observation of the apparatus during data collection. The room lights were off during data collection.

Procedure. The observer was seated and aligned with the apparatus so that the stimulus field appeared centered and maximally bright.



After instruction in the use of the laser optometer and several familiarization trials, the observer's resting measures were taken with and without the Ganzfeld and the Maxwellian view illuminated. Two consecutive measures of each resting state were collected. The order of measurement was counterbalanced across observers.

Next, the screens were presented in counterbalanced order at optical distances of 0 through 5 D in 1 D increments. At each stimulus-distance combination two successive accommodation measures were taken. In rare cases of gross instability of the accommodative responses (e.g., an absolute difference of 0.5 D or greater) observers were instructed to rest prior to repeating the two measurements. Observers were not informed of the stimulus distances. Throughout sessions observers were reminded to observe the presented stimulus carefully. The session ended with another set of resting position measures in the same counterbalanced order as the first.

### Results

The effects of screen type and distance upon the accommodative responses of the observers were analyzed by a 4-way Analysis of Variance (ANOVA). The additional factor in the analysis was a replication factor. This latter factor could serve under certain circumstances as an estimate of the error variance to test for effects involving observers. The present method of data collection results in a value

associated with this term that is perhaps a better estimate of the minimum variance achievable. Therefore, tests involving observers would appear to show reliable effects because this variance was spuriously small. In this and subsequent analyses F-ratios using this term as the denominator were not constructed. The results of this analysis are summarized in Table 1.

TABLE 1  
ANALYSIS OF VARIANCE FOR ACCOMMODATION TO THE SCREENS

<u>SOURCE</u>	<u>SS</u>	<u>DF</u>	<u>MS</u>	<u>F</u>	<u><math>\omega^2</math></u>
Screens (A)	114.3284	3	38.1095	7.45**	.09
A X C	352.6461	69	5.1108		
Distances (B)	840.1289	5	168.0258	126.72***	.54
B X C	152.4857	115	1.3260		
A X B	243.0673	15	16.2045	19.94***	.22
A X B X C	280.3532	345	.8126		
Observers (C)	496.3192	23	21.5817		
Replications (D)	21.7400	576	.0377		

\*\*  $p < .01$       \*\*\*  $p < .001$

The main effects for both screens and distances and their interaction were all reliable. Accommodation decreases in accuracy with a decrease in stimulus contrast. Furthermore, the inaccuracy is greatest at the extremes of the range tested. With the lowest contrast screen (screen 4) accommodation changes very little with stimulus distance. Figure 5 illustrates these findings.

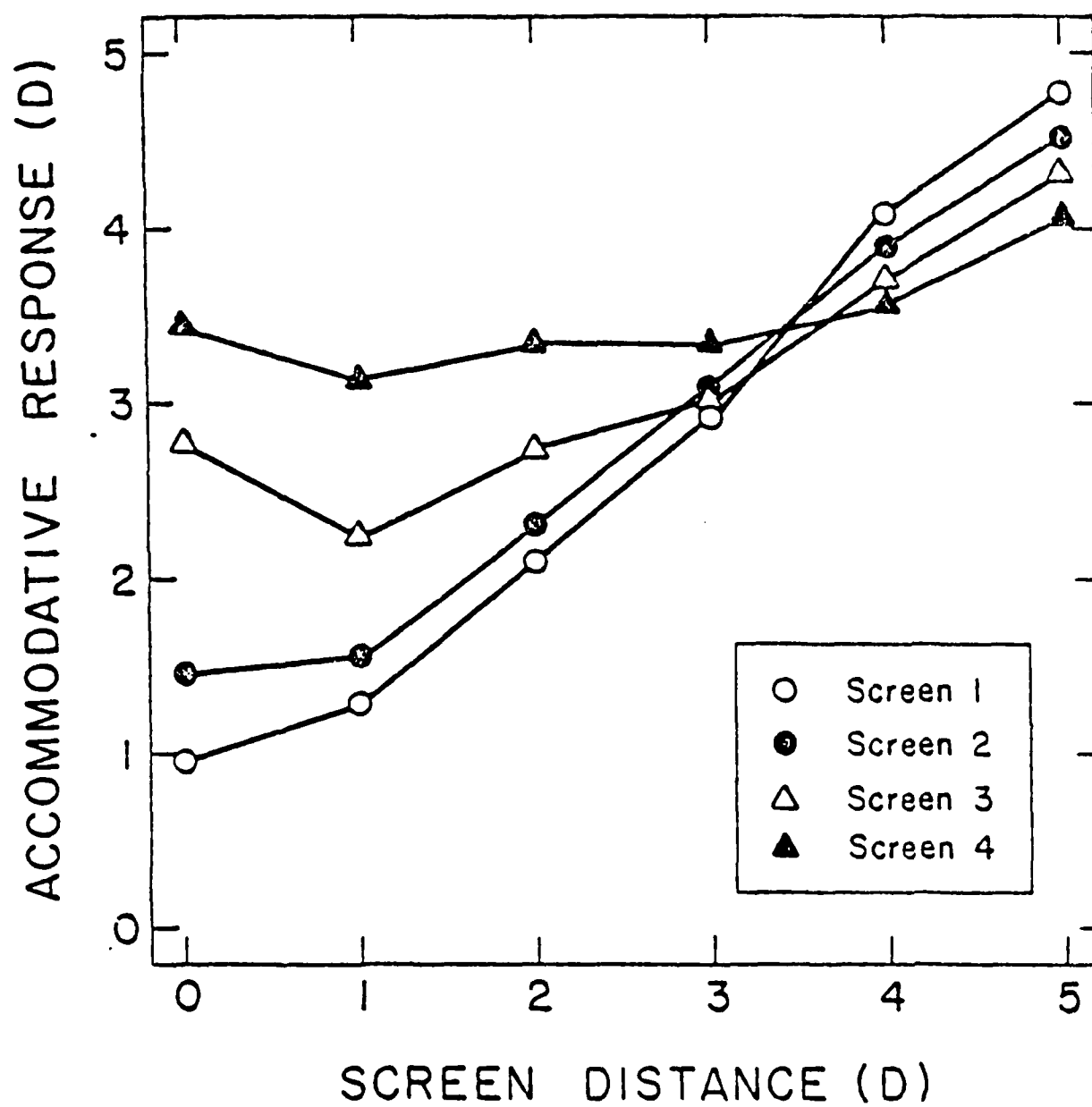


Figure 5. Accommodation as a function of stimulus presentation distance.

To assess the strength of the association between the treatments and the dependent variable, ratios were determined for the treatment variance relative to the total variance. The procedure followed that outlined by Vaughn and Corballis (1969) for designs with repeated measures. The derived ratio is equivalent to what is commonly referred to as omega squared, but the computed value tends to underestimate slightly the actual proportion of variance accounted for. Within this experiment the treatments accounted for 95% of the total variance. The screens accounted for 9%, the distances 54%, and their interaction 22%.

If accommodation had been accurate for each stimulus position, the expected mean value of accommodation across distances would have been 2.5 D. The lead and lag of accommodation were exhibited for all screens at the most extreme positions, but the overall mean response for the high-contrast screen was 2.68 D. Decreased contrast resulted in responses approaching a mean level nearly equal to the mean dark focus of 3.7 D (2.8, 3.1, and 3.5 D respectively). Figure 6 illustrates this shift from the region of accurate accommodation toward the dark focus.

Least-squares solutions were computed for the regression of mean accommodative response (over the replications) on stimulus presentation distance. Two 2-way ANOVAs were performed on the slopes and intercepts associated with each observer's responses. The results of these analyses are summarized in Tables 2 and 3 respectively.

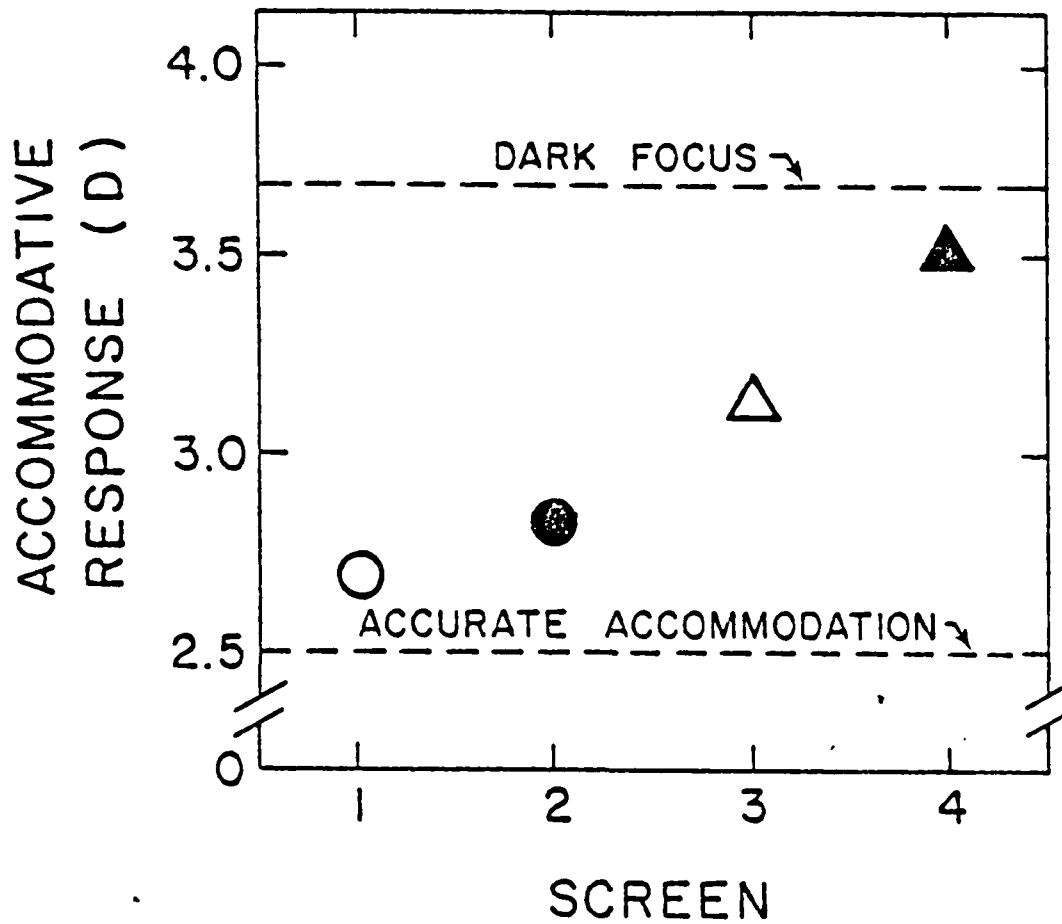


Figure 6. Mean accommodative response across stimulus presentation distances for the screen stimuli.

TABLE 2

## ANALYSIS OF VARIANCE FOR THE INTERCEPT OF THE SCREENS

<u>SOURCE</u>	<u>SS</u>	<u>DF</u>	<u>MS</u>	<u>F</u>	<u><math>\omega^2</math></u>
Screens (A)	87.2583	3	29.0861	31.52***	.49
A X B	63.6664	69	.9227		
Observers (B)	63.7084	23	2.7699		

\*\*\* p &lt; .001

TABLE 3

## ANALYSIS OF VARIANCE FOR THE SLOPE OF THE SCREENS

<u>SOURCE</u>	<u>SS</u>	<u>DF</u>	<u>MS</u>	<u>F</u>	<u><math>\omega^2</math></u>
Screens (A)	5.4496	3	1.8165	34.31***	.52
A X B	3.6531	69	.0529		
Observers (B)	2.4004	23	.1044		

\*\*\*p &lt; .001

Both intercepts and slopes differed reliably across screens ( $p < .0001$ ). The estimated magnitude of the variation due to screens in the two analyses was 35 and 41 % of the total variance respectively. A Tukey test among the mean intercepts and slopes revealed that all means differed reliably ( $p < .05$ ) with the exception of screens 1 and 2 (although these results were in the expected direction). The negative value for the Pearson product-moment correlation between slopes and intercepts supported the contention that the regression line rotates about a fulcrum ( $r(24) = -.75, p < .01$ ). Figure 7 illustrates the inverse relation between slopes and intercepts.

To determine the relationship between the accommodative fulcrum and resting positions, Pearson product-moment correlations were calculated using the median crossover point for each observer's four regression lines. Namely, the values associated with the points where the regression lines crossed the line of accurate accommodation. The median was selected as the most representative value and avoided the inclusion of extreme values that occur when the slope for an observer's regression line approaches 1.0. The median crossover was correlated with the mean (of the two measures) pre-session resting measures.

Both dark focus responses correlated reliably with the median crossover point. Although they did not differ reliably from each other, the dark focus without the light in the right eye (DF-) correlated slightly higher than the dark focus with the light (DF+). Neither light focus measure correlated reliably ( $p > .05$ ). Interestingly, the light

focus with the right eye matched for luminance (LF+) correlated slightly higher than the mismatched light focus (LF-), approaching reliability. The position of the four fulcrums may be seen in Figure 7.

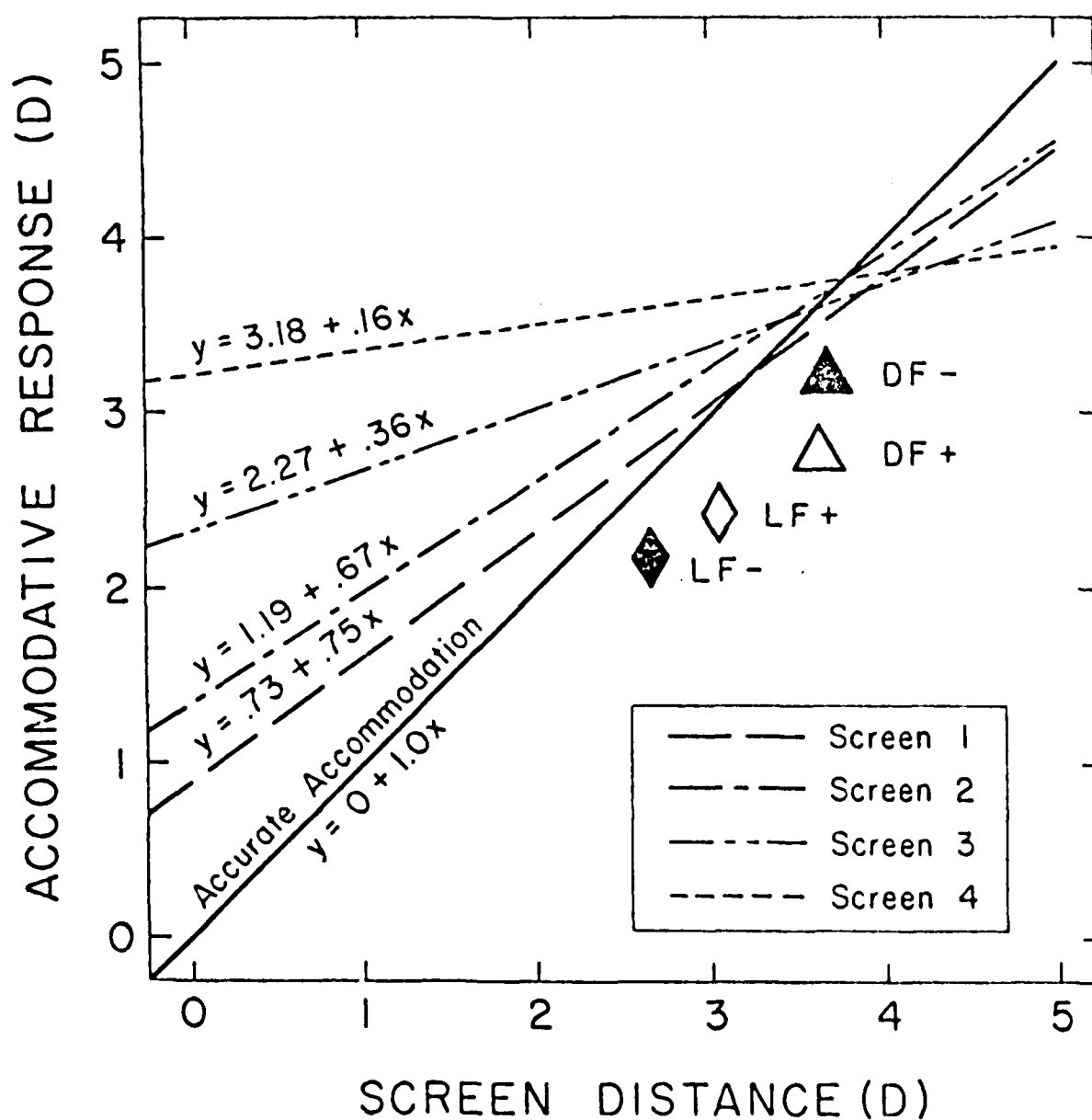


Figure 7. Regression of accommodation to the screens on stimulus presentation distance.



Table 4

## CORRELATION MATRIX FOR THE RESTING ACCOMMODATION MEASURES

	<u>DF-</u>	<u>DF+</u>	<u>LF-</u>
DF+	.91		
LF-	.72	.66	
LF+	.72	.59	.90

All the resting measures were reliably correlated with each other. Table 4 presents the correlation matrix for the resting measures. Within each type (light or dark) the measures were more highly correlated than across type. The differences between the within-type and cross-type correlations were reliable ( $p < .05$ ). Despite the reliable correlations among resting measures, mean differences appeared to exist. A 5-way ANOVA on the resting measures with dark-light focus, pre-post session, with-without right eye illuminated, observers, and replications as the factors indicated that the main effects for focus type and pre or post were reliable. The results of this analysis are summarized in Table 5. For the group mean the furthest dark focus response was nearer than the nearest light focus. Also, the mean post-session responses were always nearer than their corresponding

TABLE 5

## ANALYSIS OF VARIANCE FOR THE RESTING MEASURES

<u>SOURCE</u>	<u>SS</u>	<u>DF</u>	<u>MS</u>	<u>F</u>	<u><math>\eta^2</math></u>
Light - Dark (A)	55.207	1	55.207	16.518***	.06
A X D	76.871	23	.334		
Without - With (B)	.010	1	.010	< 1	
B X D	13.027	23	.566		
Pre - Post (D)	4.726	1	4.726	5.321*	.01
C X D	20.429	23	.888		
A X B	3.190	1	3.190	3.205	
A X B X D	22.890	23	.995		
A X C	.350	1	.350	< 1	
A X C X D	11.537	23	.502		
B X C	1.215	1	1.215	7.359*	.01
B X C X D	3.798	23	.165		
A X B X C	.338	1	.338	< 1	
A X B X C X D	8.462	23	.368		
Observers (D)	608.270	23	26.447		
Replications (E)	5.405	96	.056		

pre-session responses. These findings may be seen in Figure 8. Although these effects were reliable, the proportion of variance accounted for by the largest effect (focus type) was only 6%.

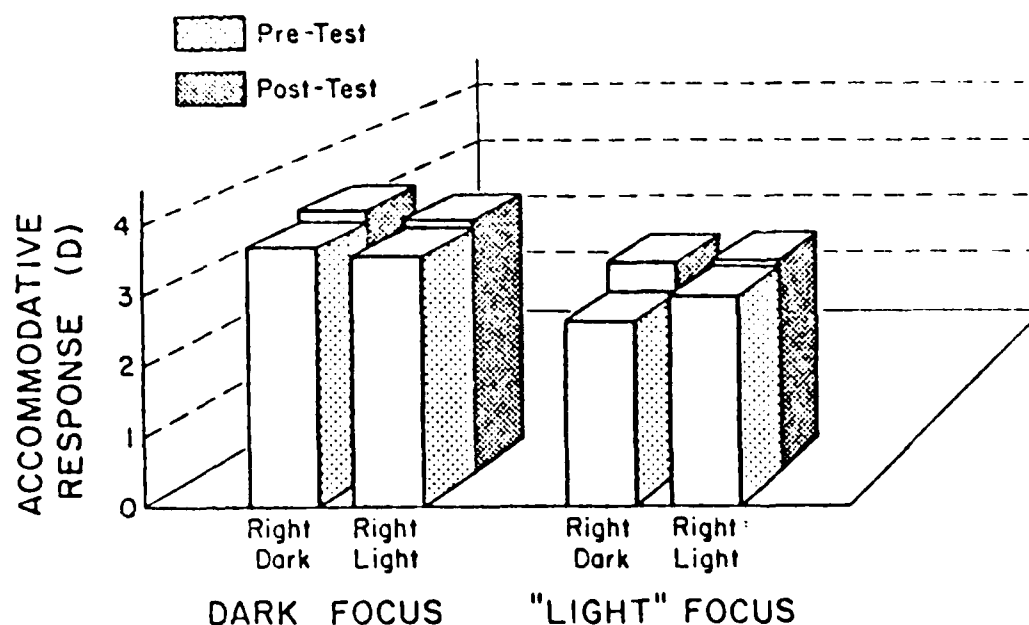


Figure 8. Dark and light focus responses with and without the right eye illuminated, pre- and post-session.

### Discussion

As was expected the accommodative responses to the high-contrast screen were reasonably accurate throughout the range of stimulus presentation distances. Consistent with the findings of Owens (1976; Note 2) and others (e.g., Charman & Tucker, 1977; 1978) some lead of accommodation was seen at the most distant position, but for the average observer relatively little lag was seen except at the near stimulus position (5 D). As screen contrast decreased, accuracy decreased when the stimulus position departed in either direction from the observer's resting accommodation distance.

The expected relationship between accommodative accuracy and stimulus resolution was hypothesized to be a useful metric for assessing stimulus adequacy (presumed to play an important role in determining the occurrence of such disruptive visual events as the Mandelbaum effect). Comparison of the derived slope for accommodative functioning and the objective change in stimulus characteristics (characterized as per cent contrast) indicates the plausibility of this technique for the functional description of stimulus adequacy. Obviously, a wider range of objective characteristics needs to be investigated prior to total acceptance of this functional metric. Nevertheless, this is an important initial step for determining the generality and applicability of the use of these computed slopes.

Individual differences did not appear to play a major role in determining the direction of the accommodative response within this experiment. The proportion of variance accounted for by treatment effects left only 15% to be attributed to observers and other sources. Likewise, slopes and intercepts appeared to be relatively independent of individual differences in the dark focus for the screens of high contrast. The higher correlations between the intercepts and the dark focus found when visual resolution of the stimulus becomes more difficult reflected the passive return toward the resting position. It is apparent that the absolute level of the accommodative response depended more on the dark focus than on the actual stimulus distance as contrast decreased.

The resting position that appeared to relate most closely to the accommodative fulcrum was the dark focus. Although this was consistent with previous research, the lower correlation between the light focus and intercept for the low-contrast stimulus was somewhat unexpected. Apparently the unresolved, low-contrast stimulus is not the same as the empty stimulus field. The absolute difference between the dark focus and light focus in this experiment was somewhat larger than that reported by Leibowitz and Owens (1978). It is possible that some characteristic of the particular viewing system affected the results. Perhaps a pure Ganzfeld might yield better correlations. Nevertheless, the ease of production of a dark environment relative to a Ganzfeld and the apparently higher predictive value of the dark focus make it the measure of choice.

The differences that did exist between the various resting measures were in the same direction found by other researchers, e.g., more distant light responses. Likewise, finding inward shifts in the resting point following such experiments is not uncommon. The magnitudes of these treatment effects were relatively small when weighed against the total variance. A variable that purports to characterize individual differences should be more related to individuals than to treatment effects. Despite the intersubject variations in the absolute level of the resting position measure, the stability of the dark focus for the short-term is quite high. The apparent stability should not be taken as license to collect such measures irrespective of an individual's prior activity. There is abundant evidence to suggest that short-term shifts in the dark focus can be quite large for some individuals (e.g., Costello, 1974; Miller, 1973).

The viewing system employed in this experiment was monocular for the left eye. Construction of an adequate binocular viewing system would not have been a trivial matter. Occlusion of the right eye from light was suspect for the Ganzfeld resting measures and a parallel could be drawn to the lighted viewing condition. The matching of luminance for the right eye was thought to be a reasonable compromise between occluding the right eye and providing a binocular viewing arrangement. However, the presence of the Ganzfeld for the right eye was considered to be a nuisance by a large number of observers. Reports of occasional difficulty in attending to the stimuli were common during the early phases of this experiment. This difficulty was probably related to

binocular rivalry and was probably exacerbated by presenting the blank field to what would be most observers' dominant eye.

## ACCOMMODATIVE SHIFTS AND APPARENT SIZE

Owens (1976; 1979) pointed out one possible confound that could cloud interpretation of Mandelbaum's findings. Varying the observer's position relative to the screen also changes the retinal image of that screen. Owens rejected the hypothesis that changes in the retinal image were responsible for the Mandelbaum effect on two grounds. First, the effect of screen distance was discontinuous, with a rather abrupt onset and offset dependent on the observer-to-screen distance. If the effect had been due to changes in the relative size or contrast of the interposed image, then a continuous effect over distance would have been seen. The individual differences in the critical observer-to-screen distance also provide evidence against the hypothesis that a specific geometric arrangement was responsible. This would have suggested a uniform effect across observers. The resting position hypothesis is indeed a parsimonious explanation but leaves unaddressed one potentially relevant dimension, namely, the adequacy of the interposed texture as an accommodative stimulus and concomitantly its ability to draw accommodation away from the target thereby creating the Mandelbaum effect.

The resolvability of the interposed texture bears on the generality of Owens' findings particularly with regard to vehicle environments. Owens had crossed two square wave gratings that were well within the range of maximum sensitivity. While spatial frequencies for which contrast sensitivity is fairly low, e.g., beyond 20 c/d or less than 0.5



c/d (Cornsweet, 1970), are unlikely to generate the Mandelbaum effect, it is not obvious, however, which stimuli will. The implication of Owens' experimental arrangement used by him and again here is that presenting resolvable details between the observer and the principal target for observation is analogous to the windscreen interposed between the vehicle operator and the external scene of intent. So, from a practical standpoint, the characteristics of interposed textures that will generate the Mandelbaum effect are of major interest.

Quite frequently the interposed texture through which observation occurs does not resemble the mesh screen employed by both Mandelbaum and Owens. Of course, exceptions include observations through actual screening, e.g., remote handling through mesh shielding or the possible application of mesh shielding as electronic emission protection in aircraft windscreens. Generally the edge contours of the interposed stimulus would be considerably attenuated. Under these circumstances a relatively more adequate target might break the involuntary pull toward the resting position. It should be noted that edge contours per se are not critical for accurate accommodation, although they may lead to a subjective impression of crisp focus. Owens may be correct in concluding that a foveal stimulus at an optical distance near the dark focus may disrupt accommodation for a fixated target at a different optical distance; however, the requisite nature for the interposed stimulus has not been defined.

In vehicle operation, dirty or streaked windscreens might be more effective in determining accommodation than distant objects, particularly when the windscreen and resting position distances correspond. However, improvements in the stimulus value of the target, alluded to above, may overcome this effect. Since most interposed surfaces are not designed to be easily resolvable and accommodation to this type of stimulus tends to yield regression slopes of less than 1, improvements in the effectiveness of target stimuli over and above the draw of the interposed surface appear possible. Such improvements might include treatments to road and runway lighting and surfaces.

Recent evidence (Iavecchia, et al., 1979) suggests that relatively near accommodation is accompanied by diminished apparent size of optically distant objects. Conversely, decreased refractive power results in increased apparent size. Although this evidence was applied to an explanation of the moon illusion, the ramifications for applied situations are evident. Any inappropriate retreat toward nearer accommodation would cause things to appear smaller and farther away (Ohwaki, 1955; Roscoe, Olzak, and Randle, 1976). Misperception of the size and distance of objects such as tail lights while driving could lead to inappropriate response latencies with attendant negative consequences. Similarly accurate perception of size and distance is critical for most aspects of flight. The relationship between inappropriate accommodation and apparent size has not been determined.

## Experiment II: Stimulus Characteristics and Accomodative Shifts

This experiment further explored the Mandelbaum effect by extending the parameters of the interposed surface to include stimuli that varied in stimulus adequacy as indexed by the slope of the regression of accommodation on presentation distance. Consistent with Owens' procedure, observers were instructed to maintain focus on the target stimulus while the screen stimulus was added to the view. Both the target and screens were presented at a variety of optical distances. The Mandelbaum effect was expected to be maximal when the most adequate screen (highest slope) was presented near the resting position and the target was presented from positions most distant from the resting position.

Individual differences were expected to play a major role in determining the occurrence of the Mandelbaum effect. The most relevant individual characteristic was hypothesized to be the resting position for accommodation that related to the crossover point described in the previous experiment. For example, an individual with a relatively distant resting position (i.e.,  $<1.0$  D) was expected to show relatively little change in accommodation when the target was at optical infinity irrespective of changes in the screen distance and coincidentally little change in apparent size. On the other hand, observers with nearer resting positions were expected to show larger accommodative and apparent size shifts as the screen approached the resting position distance. The converse was expected for the nearest target distance.

Therefore, this experiment was designed to examine the relationship between stimulus adequacy and the Mandelbaum effect. The stimuli from Experiment I were presented at varying optical distances while the observer attempted to maintain focus on an adequate target also presented at varying optical distances. While the observer viewed the target, the accommodative state was measured with the laser optometer both with and without the screen stimulus.

#### Method

Observers. The observers from Experiment I served in this experiment.

Stimuli. Screen stimuli from Experiment I served as the interposed surfaces. The target stimulus consisted of a 3 x 3 matrix of Snellen Es subtending 4.9 deg on a side. The individual letters subtended 1.3 deg and had a stroke width of 15.6 min. The matrix was reproduced as a high contrast photographic transparency with black letters on a clear background.

Apparatus. The apparatus from Experiment I was used for this experiment.

Procedure. The four screen stimuli were presented at optical distances of -0.63, 0.63, 1.88, 3.13, 4.38, and 5.53 D. The target stimulus was placed at 0, 1.25, 2.50, and 3.75 D. The order of

presentation of screen stimuli and distances was counterbalanced across observers. The experiment was divided into sessions conducted on four successive days. On a given day the observer saw the counterbalanced screen type and distance presentation for only one target distance. The order of presentation of target distances was counterbalanced across observers.

Observers were seated and aligned as in Experiment I. The matched dark and light focus resting measures of accommodation were taken both before and after data collection. Within the session stimuli were presented sequentially. At the start of a trial the target stimulus was placed at the appropriate distance in Channel 2. While viewing this stimulus the observer's accommodation was measured twice using the previously described bracketing technique. Next, while the observer viewed the target and the screen that had been added to Channel 1 at the appropriate optical distance accommodation was measured twice. This procedure was repeated for all screen and distance combinations for that session. Then the observer's accommodation was measured while he again viewed the target alone. Observers were instructed to rest briefly between trials and were allowed to rest as necessary to avoid excessive fatigue.

TABLE 6

ANALYSIS OF VARIANCE FOR ACCOMMODATION TO THE TARGET WHEN  
THE SCREENS ARE PRESENT AT VARIOUS DISTANCES

<u>SOURCE</u>	<u>SS</u>	<u>DF</u>	<u>MS</u>	<u>F</u>	<u><math>\omega^2</math></u>
Screen Type (A)	44.327	3	14.776	2.81*	.02
A X D	36.327	69	5.265		
Target Distance (B)	2597.827	3	865.942	176.95***	.61
B X D	337.661	69	4.894		
Screen Distance (C)	138.932	5	27.786	33.63***	.06
C X D	95.015	115	.826		
A X B	107.558	9	11.951	9.09***	.06
A X B X D	272.139	207	1.315		
A X C	69.340	15	4.623	7.01***	.04
A X C X D	227.493	345	.659		
B X C	24.924	15	1.662	2.97**	.01
B X C X D	193.040	345	.560		
A X B X C	26.019	45	.578	1.32	
A X B X C X D	454.464	1035	.439		
Observers (D)	1101.895	23	47.908		
Replications (E)	87.052	2304	.038		

\*  $p < .05$

\*\*  $p < .01$

\*\*\*  $p < .001$

## Results

The accommodation data under the Mandelbaum condition were analyzed by a five-way ANOVA with replications (two per observer per condition), target distances, screen distances, and screen type as the fixed independent variables and observers as the random variable. The main effects for screens, target distances, and screen distances and their first-order interactions were all reliable ( $p < .05$ ). Target presentation distance accounted for 51% of the total variance. The various effects for screens, screen distances, and their interactions accounted for nearly an additional 20% of the total variance. The results of this analysis are summarized in Table 5.

Figures 9 and 10 illustrate the effects. For the two high-contrast screens (1 and 2) the effect of screen position on accommodation was quite evident. As the screen position approached the dark focus it tended to draw accommodation away from the target position. Additionally, the screen appeared to be a more potent stimulus than the matrix of Es under certain circumstances. For example, when either screen 1 or 2 was more distant accommodation was drawn outward from the target at 3.75 D. However, neither lower contrast screen (3 or 4) appeared to exert much influence on the accommodative response to the target.

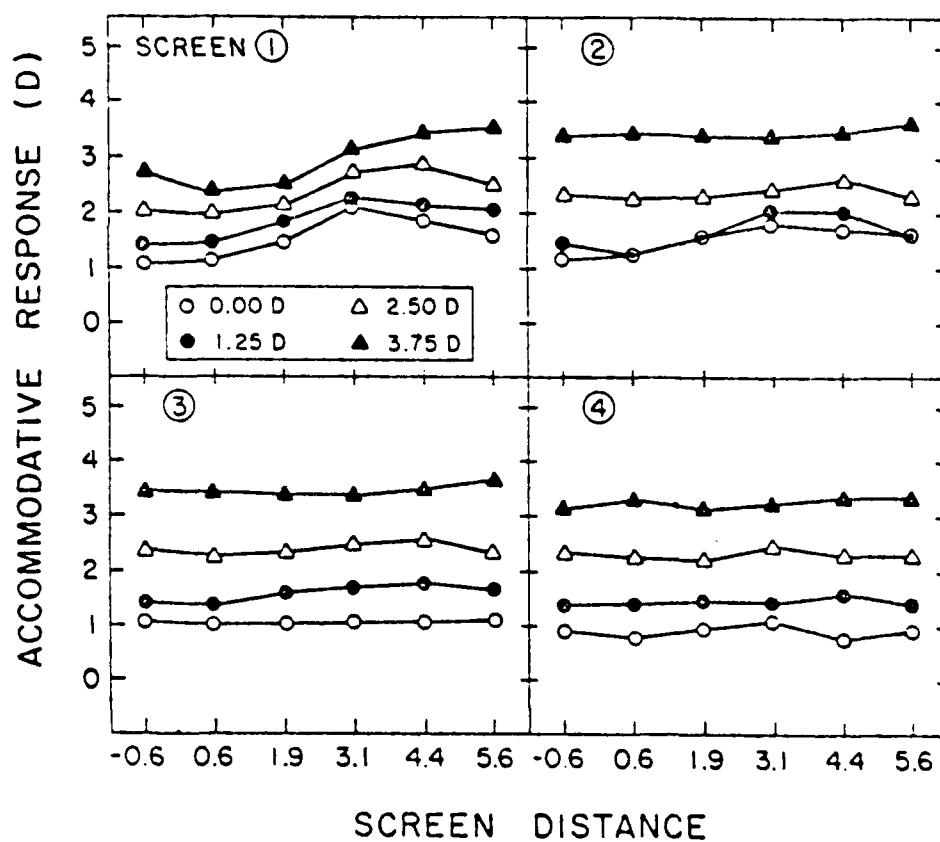


Figure 9. Accommodative responses to target at various distances with simultaneous presentation of screen. Key refers to target distance.



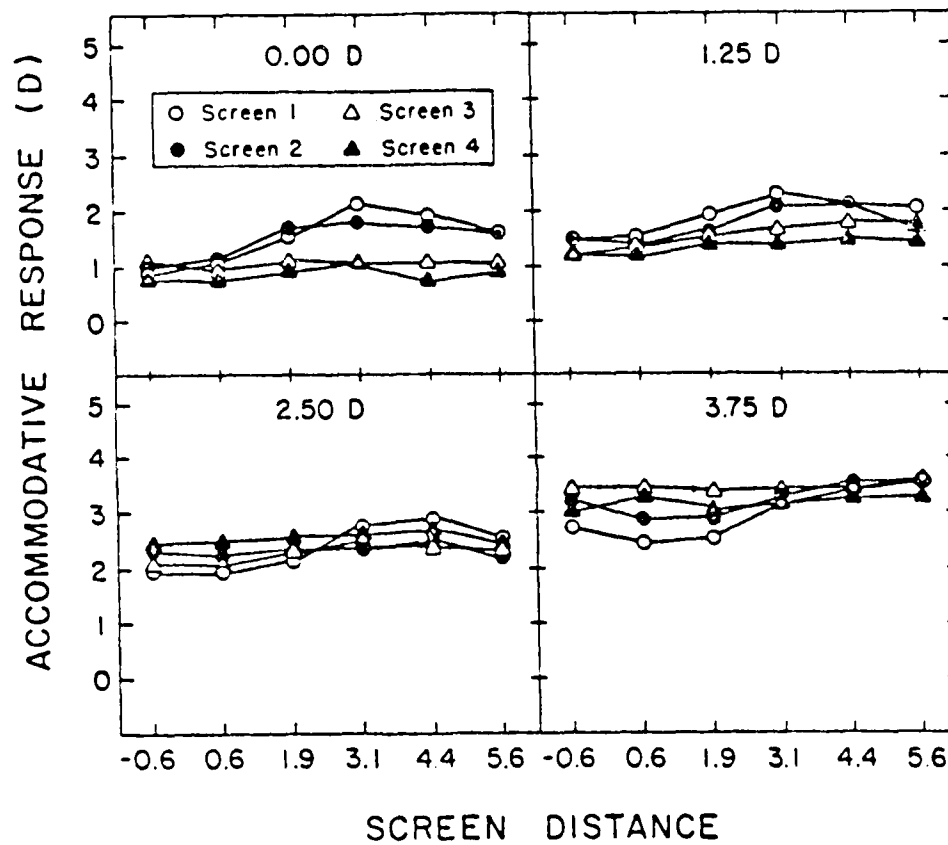


Figure 10. Accommodative response to target presented at various distances with simultaneous presentation of screens.

### Discussion

It was expected that interactions would exist between target and screen distances. The target would be relatively less effective in stimulating accommodation to its distance when the screen was presented nearer to the resting position. Likewise, this was expected to interact with stimulus adequacy. The finding of an outward shift from the near target position (and the mean dark focus distance) was not expected. This effect is probably related to the peripheral surround effect described by Hennessy and Leibowitz (1971). In this case not only were there peripheral cues, but the screen was superposed over the entire stimulus field. Careful inspection of Owens (1979) reveals a similar trend existed for his observers also. There was a pull toward the screen position even when the target was placed at the observer's dark focus, but the effect is rather small.

The resting position was expected to play a major role in determining the magnitude of the effects of the other variables under differing conditions. In fact, nearly all observers (19/24) exhibited at least some shift when the screen was positioned near their dark focus and the target was at 0 D. Relatively little change was seen for most observers when the target was at the nearest position, but the mean dark focus was nearly equal to that distance.

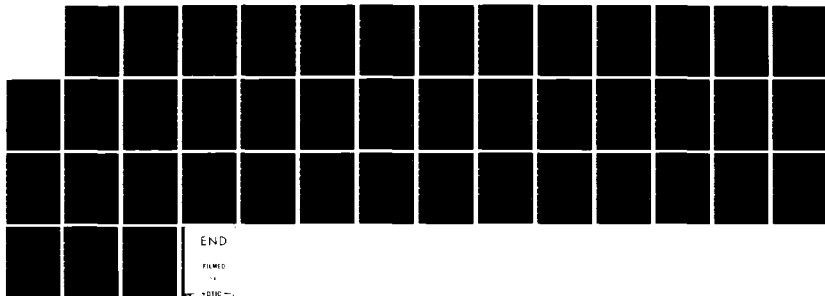
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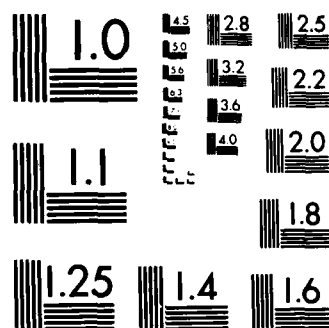
VISUAL ACCOMMODATION THE MANDELBAUM EFFECT AND APPARENT  
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### Experiment III: Qualitative Size Changes

The demonstration by Hoffman (in Ogle, 1950) indicates that inward shifts in accommodation are accompanied by decreases in the apparent size of distant objects. As Hoffman pointed out, objective measurement of such shifts in size is difficult. Although the appearance of an object changes, any measuring standard placed with the object changes equally. Under these circumstances, the objective size would remain constant despite the subjective impression of a shrunken appearance for both object and standard. The converse of this was not explicitly discussed by Hoffman, but follows naturally from his demonstration. An outward shift in accommodation should be accompanied by an increase in the apparent size of the object being viewed.

This experiment was designed to investigate the co-occurrence of accommodative shifts due to the Mandelbaum (and its reverse) effect and shifts in the apparent size of an object. In accord with the findings of Owens, accommodation should shift at least slightly both inward and outward from the target distance under the appropriate stimulus configurations, and these shifts should result in decreases and increases respectively in the apparent size of the target.

#### Method

Observers. The 24 observers from the previous experiments served in this experiment.

Stimuli. The target and high-contrast screen stimulus from the previous experiment were used.

Apparatus. The same arrangement was maintained for this experiment.

Procedure. The procedure was similar to the previous experiment. The screen and target distances from the previous experiment were used. The order of screen and target distance presentation was counterbalanced across observers. The stimuli were presented sequentially. First, the observer viewed the target stimulus alone and accommodation was measured. While the observer continued to view the target the screen was added rapidly at the appropriate distance. The observer was instructed to observe the target matrix and report any change in the apparent size of the matrix that occurred with the insertion of the screen. The observers were encouraged to make this report as soon as possible following the insertion of the screen. Three responses were allowed; larger, smaller, and no change.

This procedure was repeated for each screen position at that target distance and accommodation was then measured for the target alone prior to moving the target to its next position. This procedure yielded 24 accommodation and apparent size judgments for the Mandelbaum conditions. Two matched light and dark focus responses were taken at the beginning and end of each session.

## Results

The data for each observer were separated into the three judgment types. Three separate analyses were then conducted to determine the co-occurrence of accommodative shifts and apparent size changes. For the 23 observers who reported at least one smaller judgment, seventeen of those observers had a majority of the accommodative shifts in a nearer direction on the trials in which they said "smaller" the judgment of smaller apparent size following insertion of the screen. Of these, 17 had a majority of near accommodative responses. A binomial test indicated that a result as extreme as this would occur with a probability of .02. For observers reporting at least one larger judgment, 16/20 had a majority of more distant accommodative responses when these shifts occurred ( $p < .01$ ). When no apparent size change was reported, the shifts in accommodation were nearly equally divided; 10 further, 12 nearer, and 2 no change ( $p > .05$ ).

Data of this type with repeated measures is difficult to analyze further because of a lack of independence of judgments. Nevertheless, the percentages of total judgments (unweighted across observers) follows the same pattern as the above data. When observers reported an increase in apparent size, accommodation had shifted to a more distant plane on 75% of those trials. Conversely, when apparent size was judged to have diminished, accommodation drew nearer on 59% of those trials. The corresponding percentages for trials on which no change in apparent size was reported were 56% nearer and 44% further shifts in accommodation.

### Discussion

Although these data were based solely on subjective report, they provide sufficient evidence to support the contention that shifts in accommodation under the Mandelbaum effect are related to those described by Hoffman. Moreover, the reverse Mandelbaum effect (hyperopic shift) was shown to be related to increases in apparent size. The lack of bias toward either further or nearer accommodation when no change in apparent size was seen also supports the contention that accommodation and apparent size are related.

Random fluctuations in the accommodative response were expected to occur. The ciliary muscle, like other physiological systems, seldom assumes a truly constant level. These fluctuations are reflected in the even split between near and far accommodative shifts that occurred when apparent size was reported to be unchanged. A continuously recording optometer sampling according to a computer controlled algorithm might have avoided some of the problems inherent in the laser optometer. The finite time required to actually make the accommodation measurement with a discrete device like the laser optometer inevitably insures a small delay will exist between the verbal response and the accommodation measure. Nevertheless, the overall results were quite consistent with the hypothesis.

Observers often volunteered comments that supported Hoffman's contention that the measuring instrument would appear to shrink as well.



Most reported that the entire field would appear to shrink on occasion. Many also reported that the task proved to be difficult at times. Apparently momentary shifts in accommodation often provided momentary shifts in the apparent size of the target. However, the discrimination between the random changes and those induced by the stimulus conditions were apparently successful.

As a practical matter, increases in apparent size are relatively unimportant for most vehicle control environments. The mean distance for object observation will generally exceed both the dark focus and the distance of surfaces such as windscreens. On the other hand, the hyperopic shifts could be somewhat analogous to situations in which the target and background are at different distances. A distant textured background would have an effect similar to the more distant screen condition.

#### Experiment IV: Quantitative Size Changes

If under certain circumstances accommodation is inappropriate for the object being viewed, that change in accommodation has been shown to relate to a change in the subjective appearance of the size of an object. The inappropriate accommodation that occurs under the Mandelbaum effect has not been related to changes in the measurable size of an object. This experiment was designed to investigate the

occurrence of quantifiable changes in the apparent size of an object when accommodation changes.

Once again, individual differences should play a role in determining the occurrence of both shifts in accommodation and apparent size. The apparent size of an object is presumed to remain relatively constant when accommodation remains unchanged. In the previous experiments and in the work of Owens it had been found that individual differences appear to exist in susceptibility to the Mandelbaum effect.

Recent research (Iavecchia, et al., 1978; Simonelli & Roscoe, 1979) has also shown that the apparent size of an object may relate to the magnitude of an individual's accommodative response. For a small sample Simonelli and Roscoe found that the correlation between accommodation and a simulated zenith moon was very high ( $r = .90$ ). Iavecchia, et al. found a similar correlation between apparent size (of a moon-like disc) and distance of accommodation. Therefore, it was expected that the apparent size of an object would relate to the distance of accommodation and that this relationship would continue following shifts in accommodation. The apparent size of an object should shrink measurably if accommodation shifts to a nearer plane of focus.

#### Method

Observers. Twelve volunteers (eight of whom served in the previous two experiments) were selected to participate in this experiment. The four additional observers met the same acuity criteria and had served in previous similar experiments.

Stimuli. The screen used in this experiment was a black fiberglass mesh window screen tightly stretched in a wooden frame. The external scene that the observer viewed was essentially identical to that used by Iavecchia, et al. (1978). Basically, it was the view looking east from the fifth floor window of the research wing of the Psychology Building on the Urbana-Champaign campus of the University of Illinois. The field of view was filled with trees and various buildings to the horizon (actually the roof of a distant building). The window (at 2.0 m) through which observation took place had been recently cleaned.

Apparatus. Two separate pieces of apparatus were interfaced for this experiment. A modified version of the laser optometer was mounted to the left of a stimulus presentation box. An external view of the apparatus may be seen in Figure 11. A cut-away view of the optometer is presented in Figure 12. The stimulus presentation box has been described in detail elsewhere (Iavecchia, et al. 1979). It provided a simulated "moon" that could be combined optically with an external scene and a variable diameter comparison moon. Figure 13 shows the box in its two separate modes, one for viewing both the external scene with collimated moon and the other for adjusting the comparison moon.

The chin and forehead rest were not used to position each observer. The beamsplitter was mounted behind an eye-shaped cut-out. Observers placed their eye within this to insure that each was in the same position. The possible differences in eye position among observers were limited to the minor variations in the anatomy around and within the

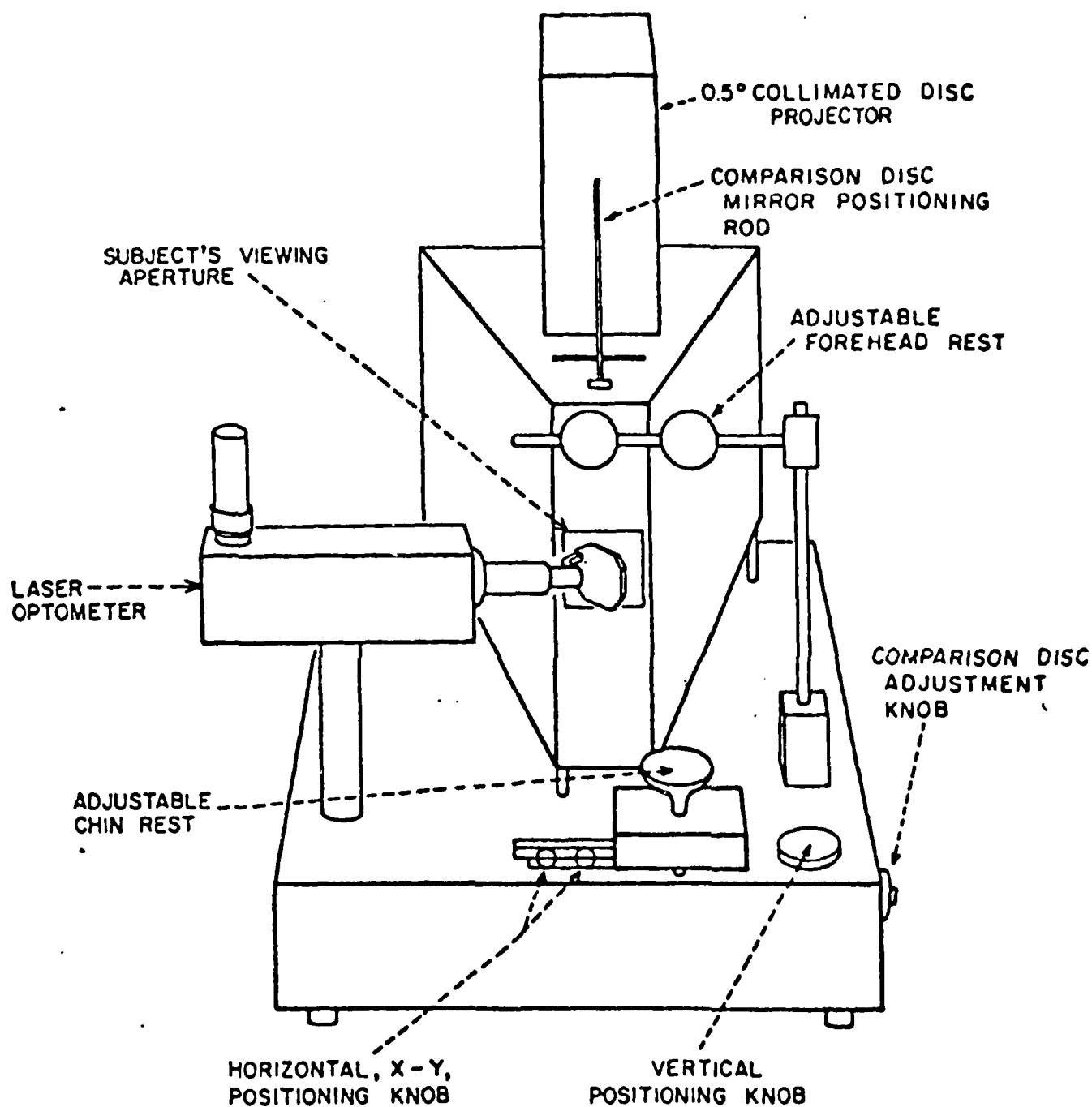


Figure 11. Perspective drawing of the stimulus presentation box with the laser optometer in place.

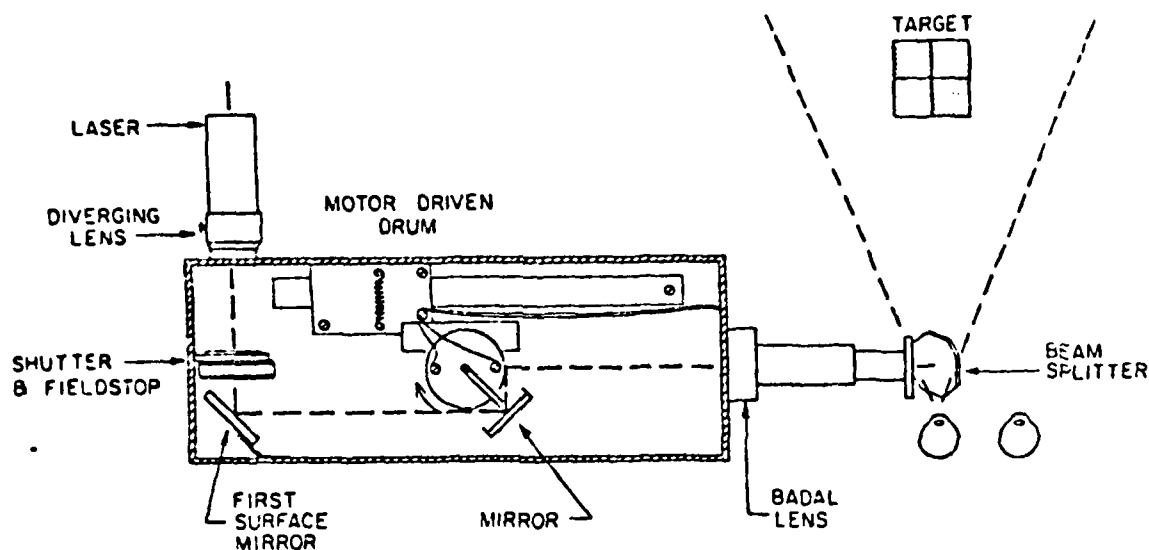


Figure 12. Cut-away schematic of the modified laser optometer.

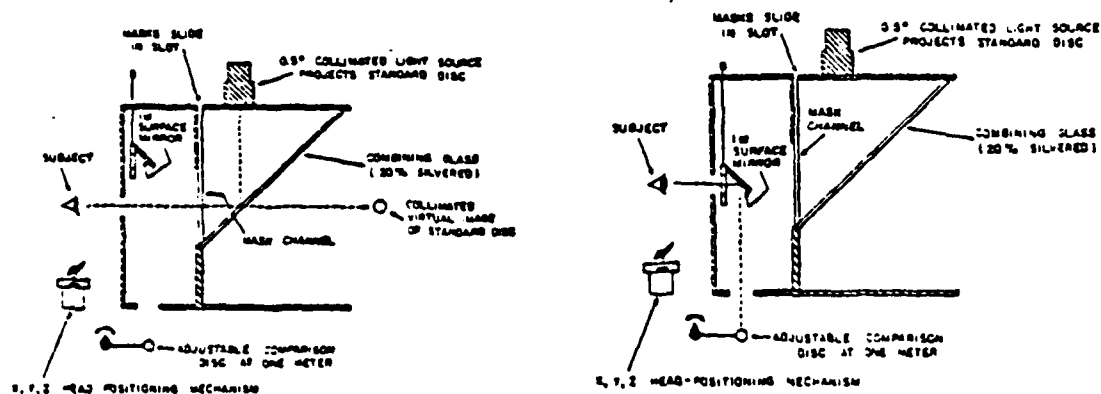


Figure 13. Cut-away schematic of the stimulus presentation box. On left box is set for viewing visual scene with collimated lighted disc superposed. On right for viewing adjustable comparison disc.

eye. A field stop immediately behind the beamsplitter slightly attenuated the field of view to 37 deg VA. The near position of the field stop would have required in excess of 25 D of accommodation for resolution. Therefore, this would not affect the accommodative response. This out-of-focus edge insured against the possibility of an observer's responding to the frame of the screen that would have been visible in the far periphery.

Procedure. Observers were given sufficient information for the tasks, but were not told the hypothesis involved. They were shown the similarity between this arrangement and the previous apparatus and instructed in the use of the size-matching apparatus. The explicit instruction given all observers was to make the adjustable moon appear be the same size as the collimated moon. They were further instructed to treat each trial individually and not to make their judgments relative to any previous condition. For each measurement the observer was allowed to refer to the collimated moon a maximum of three times.

Preceding and following each session the dark focus was measured for each observer. To create a dark environment an opaque cloth shroud was attached to the observer's side of the apparatus (this also served to eliminate extraneous light during data collection), the moons were turned off, and an opaque shield was attached to the exit side of the box. The session began and ended with two accommodation and apparent size matches to the external scene and moon without the screen. The

screen was presented twice sequentially at each of four distances (.75, 1.5, 2.25, and 3.0 D) and accommodation and apparent size measures were collected at each distance. The order of presentation was counterbalanced across observers. The screen was moved while the mirror reflecting the adjustable disc occluded the external scene. This prevented the observer from knowing with any degree of certainty the precise distance to the screen.

### Results

Two two-way ANOVAs summarized in Tables 7 and 8 were performed on the accommodation and apparent size data. The effect of screen distance was reliable in both analyses. However, the screen position accounted for a relatively small proportion of the variance in both analyses (19 and 8% respectively). These proportions are similar to that found in the previous experiment.

The relationship between accommodation and apparent size was analyzed by a series of Pearson product-moment correlations. For the initial control situation (no screen) the correlation between an observer's accommodation and apparent size judgment was reliable ( $r = -.56$ ,  $p < .05$ ). This negative correlation indicates that apparent size decreases when accommodation draws nearer. The same relation was found across the four screen conditions,  $r(48) = -.76$ ,  $p < .01$ . The relationship between the mean accommodative response and the mean apparent size judgment for each condition is illustrated in Figure 14.

TABLE 7

## ANALYSIS OF VARIANCE FOR ACCOMMODATION

<u>SOURCE</u>	<u>SS</u>	<u>DF</u>	<u>MS</u>	<u>F</u>	<u><math>\omega^2</math></u>
Screen	4.459	5	.892	8.139***	.19
A X B	6.026	55	.110		
Observers (B)	27.664	11	2.515		

TABLE 8

## ANALYSIS OF VARIANCE FOR APPARENT SIZE

<u>SOURCE</u>	<u>SS</u>	<u>DF</u>	<u>MS</u>	<u>F</u>	<u><math>\omega^2</math></u>
Screen	10870.069	5	2174.014	6.354***	.08
A X B	18819.764	55	342.188		
Observers (B)	72926.819	11	6629.711		



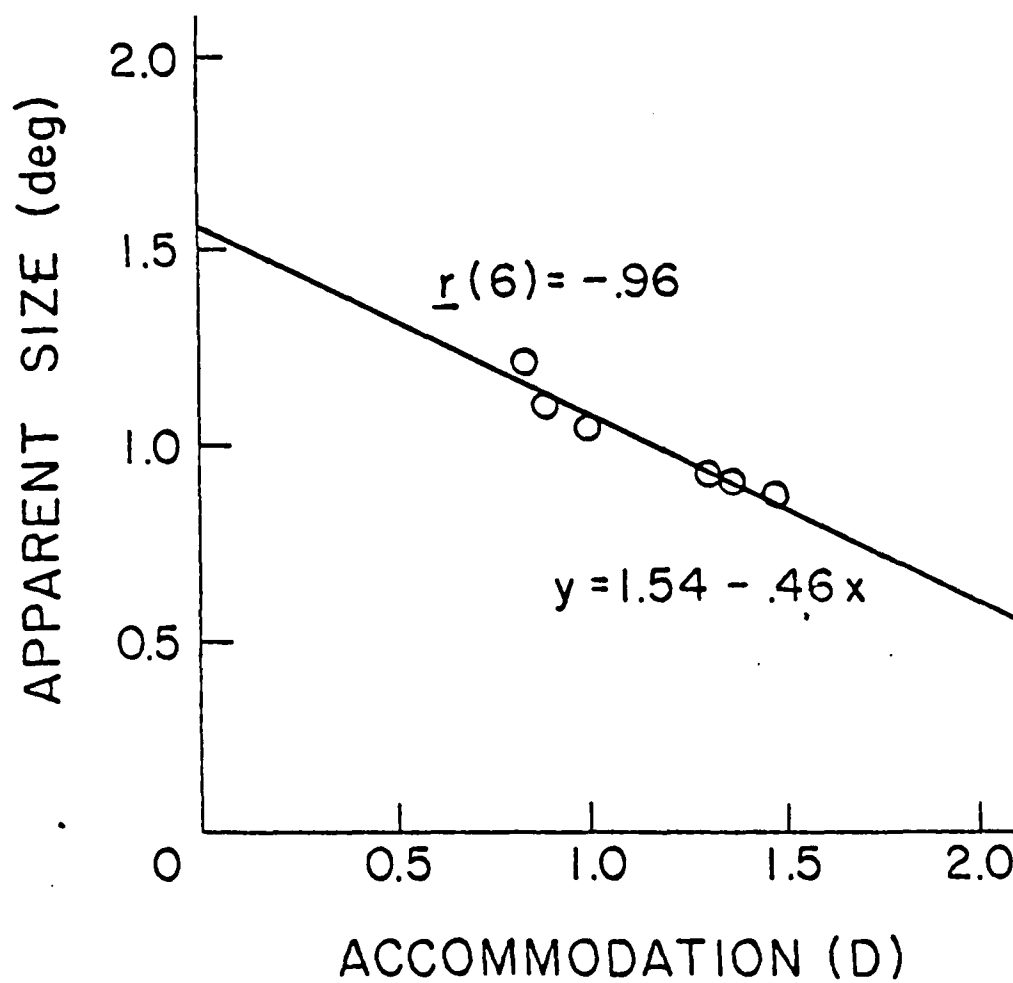


Figure 14. Apparent size as a function of accommodation. Each point represents the mean of 12 observers.

### Discussion

The monotonic increase in mean accommodation and decrease in mean apparent size as the screen position approached the observer combined with the relatively high correlation between apparent size and accommodation suggest that accommodation may be a prominent factor in determining the apparent size of an object. These data are consistent with previous research (cf. Iavecchia, et al., 1973; Simonelli & Roscoe, 1979). The sum of these studies supports the contention that the distance to which an observer is accommodated has a real, quantifiable effect on apparent size. Although this is not to be taken as an exclusive factor, the magnitude of the correlations between apparent size and accommodation found in these experiments indicates that a large proportion (approximately 50% in the current study) of the total variance may be attributed to accommodation.

## GENERAL DISCUSSION

Theoretical Issues

Charman and Tucker (1978) have shown that a decrease in contrast modulation of sine-wave stimuli can result in very inaccurate accommodative responses, particularly when such stimuli are low in frequency (e.g., 2.0 or 0.67 c/d). The data from one highly practiced observer suggest that a contrast modulation of 10 to 15% is the point at which accommodative accuracy to a stimulus at 1.4 D begins to decline rapidly. The response then approaches the observer's dark focus. In the first experiment presented here, the effect of stimulus blur is similar to contrast modulation and the stimulus appears to become effectively a low-contrast stimulus of 2.3 c/d. However, Charman and Tucker (1977) point out that the response to multifrequency targets is not easily predicted from a knowledge of component frequencies and the accommodative response to those individual frequencies. This apparently reaffirms the need for a metric that is not dependent wholly on objective characteristics.

The relative independence of the slope of the regression line relating accommodation to stimulus presentation distance from an individual's dark focus provides additional support for the accommodative fulcrum proposed by Johnson (1975). The relation of intercepts to the dark focus suggests that the dark focus is the

position for the fulcrum. The minor deviation of the dark focus from the point of the fulcrum probably relates to the differences in the conditions noted by Benel and Benel (1979). The stimulus conditions are always lighted and approximately 0.3 D of accommodation increase occurs when the eye goes from a true Ganzfeld to the dark (Leibowitz & Owens, 1975). This supports an earlier contention (Wald & Griffin, 1947) that 0.3 to 0.5 D of accommodation is due to the Purkinje shift from bright to dim light.

The role that the dark focus plays in determining accommodative accuracy and the occurrence of the Mandelbaum effect is quite evident. Accommodation is most accurate near an observer's dark focus and becomes decreasingly so as the stimulus position departs in either direction from this position (the lead and lag of accommodation). These data are consistent with Toates' (1972) hypothesis of a proportional controller for accommodation. As the target moves further from the dark focus, greater error is tolerated. Therefore, the dark focus can be used to predict the region where an individual will accommodate most accurately to the stimulus. The dark focus is also predictive of the distance to which an individual will accommodate when the stimulus has not been resolved.

The stability of the dark focus across time is quite high. In the short-term the correlation between successive measurements will be high if all else remains equal. Rarely would conditions be considered precisely the same (the passage of time itself has occurred) and the

effect of participation in experiments has been shown to increase the mean dark focus slightly from the pre- to post-session measurements. Short-term changes can be extreme if environmental or intraorganismic factors change dramatically. Miller (1978) has shown that the long-term changes in the dark focus are relatively small on the average, but some individuals exhibit extreme lability in the dark focus that appears to relate to personality factors unique to those individuals.

The influence of accommodation in apparent size is not well established. Controversy continues over which of the several oculomotor adjustments is primarily responsible for a change in apparent size. The effect of pupil diameter is rarely considered to be an important factor. The primary factors are considered to be convergence and accommodation. The mechanism whereby either of these factors could influence apparent size is undefined. Presumably, the influence of convergence would be on some central scaling mechanism. Likewise, accommodation could effect size changes through a similar mechanism. Alternatives to this include peripheral changes relative to the retinal projection of the object.

Roscoe and Benel (1973) presented one possible alternative to the constant retinal projection position. The effect of increasing the refractive power of a convex lens is a decrease in the image size. The image size of objects subtending equal visual angles projected from various distances is assumed to remain constant. This assumption is based on certain aspects of the reduced schematic eye. The magnitude of any size changes due to this increase in refractive power is difficult

to estimate, because internal adjustments within the eye are assumed to keep image size nearly constant.

A second possible cause of image size changes has been suggested by Enoch and his associates. Enoch (1973) reported a phenomenon related to a very near accommodative response. Under marked accommodation the area of the retina increased 2.4%. Retinal stretch occurred with exertion of the ciliary muscle. The amount of stretch was sufficient to pull the retina toward the ciliary body. Blank and Enoch (1973) reported inaccuracy in bisection of a line related to the asymmetry of the stretch of the nasal and temporal hemispheres. Likewise, inaccuracies in the perceived extent of objects should occur in general. When accommodation for an object of fixed visual angle is substantially increased, it will be perceived as being smaller. The image covers fewer receptors and is interpreted as being proportionally smaller.

In the present experiment the effect of the latter alternative presumably would be small. A more likely explanation for the effect concerns a central mechanism. This mechanism relates to the idea of corollary discharge or efferent copy. The command to execute some change in the state of a peripheral organ is accompanied by an internal reference signal. A signal to the ciliary muscle to execute an increase in accommodation is accompanied by a signal to maintain proper scaling of size relations. In the absence of such changes in the peripheral organ (such as would occur under cycloplegia or in presbyopes) the change in apparent size would still occur. This presumably explains the

findings of Heineman, Tulving, and Nachmias (1959) who found that homatropine had no effect in reducing the shift in apparent size that occurred with distance and that presbyopes reported size changes similar to those reported by normal observers.

Hollins (1975) assumed that Heineman, et al. had eliminated accommodation by preventing the response from occurring. He proceeded to test the effects of convergence "alone." The constant level of accommodation was inferred from the subjective report of target clarity, a tenuous measurement at best. A wide range of focus is acceptable to most observers as being clear (cf., Charman and Tucker, 1978). In a second condition, Hollins assumed further that his makeshift retinoscopic measure approached accuracy, although he reported that the measurements were only approximate. The use of pinholes and ophthalmic lenses to induce accommodation changes is also questionable. Viewing through pinholes has been shown to reduce accommodative accuracy (Renessy, et al. 1975) and accommodation induced by ophthalmic lenses is surprisingly inaccurate (Randle, Roscoe, and Pettit, in press).

In a similar experiment Alexander (1975) reported relatively small changes in the apparent size of objects that he attributed to the minification factor of the ophthalmic lens employed to induce accommodation. Despite his conclusion that accommodation plays a minimal role in micropsia, the condition in which accommodation was allowed the greatest range (monocular viewing without conflicting convergence cues) induced the most pronounced micropsia. Once again,

the actual accommodative state associated with the use of ophthalmic lenses was not verified, but assumed to follow accurately the nominal requirement of the lens.

Perhaps, it is simplistic to look for a single mechanism underlying apparent size. The complexity of the perceptual process probably dictates that multiple sources of information be employed. Under most circumstances redundant cues are available, but the cues available in most experimental contexts are an abstraction. It is quite likely that the particular cues being provided may determine the mechanism that is responsible for a phenomenon in a given context. In other contexts with different cues available, the inherent adaptability of the perceptual system gives it the appearance of making sole use of a different mechanism. The system works with the available cues, and it is obvious that apparent size depends on many factors including experiential.

#### Practical Aspects

The loss of accommodative accuracy concomitant with increased stimulus blur (lowered contrast) is certainly consistent with a growing body of literature on the factors influencing accommodation. These factors include reduced luminance (Johnson, 1976), lowered contrast modulation of sine-wave stimuli (e.g., Charman and Tucker, 1973), or targets approaching the extremes of the range of visual sensitivity (e.g., Owens & Leibowitz, 1975; Benel & Benel, 1979). The slope of the



function relating accommodation to stimulus presentation distance apparently provides a plausible means for the functional description of stimuli that differ in their objective characteristics.

The relative independence of these slopes from individual differences suggests that the metric has sufficient generality to be worthy of testing in a wider variety of contexts. Additional work is needed to determine more completely the relationship between the functional and objective description of stimuli. The development of a metric that could be applied across various stimuli would simplify certain design decisions in applied settings. It would, however, require the collection of behavioral data that extend beyond the realm normally considered in those contexts.

The relationship between the slope of the accommodative function and the occurrence of the Mandelbaum effect was as predicted. Namely, stimuli that in isolation had relatively little effect on accommodation did not induce accommodation to shift from the target distance. The greater the slope, the more likely it was that an individual would show a shift in accommodation when the screen was presented near the observer's dark focus and the target was relatively disparate from that distance. Although the limits of this phenomenon were not completely determined in this experiment, it is apparent that a slope exists for which some percentage of observers would show little or no shift. From a practical standpoint this particular slope is very important. Much like other design considerations, the precise values of the parameters

that can be accepted depend on the situation. Prescriptions for the myriad situations are not possible here. Another factor that should not be overlooked is the adequacy of the target. The present study could be viewed as a "best" case, and decreases in target adequacy would presumably dictate that lower slopes be accepted for the interposed texture.

The practical situations in which data on interposed texture would be important were alluded to earlier. The ubiquitous automobile windshield, depending on its condition, provides varying amounts of texture. It might be desirable to set objective standards based on a functional metric that could be applied to determine the acceptability of a given windshield. This would be most easily applied prior to installation, but in the case of existing automobiles state inspection stations could apply the standard. Scratches and perhaps chemically induced etching from environmental sources are relatively permanent problems and would be the target of such a program. Of course, a large amount of texture available on windshields is temporary and may be corrected by the simple expedient of removing the dirt.

Aircraft operation presents several unique problems. Aircraft windscreens are scratched much more frequently. In addition, the objects of interest are often more difficult to see (e.g., air-to-air search for other aircraft). The requirement for accurate, unrestricted viewing of the object of interest is probably even more important in aircraft than automobile operation. There is one major advantage for

aircraft over automobiles, the fairly thorough inspection which aircraft undergo periodically. The cost of an additional inspection program would have to be weighed against the potential benefits.

While the loss of acuity that occurs with misaccommodation is important, the demonstrated relationship between accommodation and apparent size implies that size cues may depend on several factors. A small change in the accommodative draw of an interposed surface may be sufficient to change the apparent size of an object even with all other factors held constant. This applies to familiar as well as unfamiliar objects. The size of the back of an automobile may be a salient feature of the highway environment and presumably influences decisions as to when to apply breaks or change lanes when overtaking. If a familiar object is perceived as being smaller it will also be perceived as being more distant (Hennessy, 1975). An obvious consequence of this would be a delay in reaction.

This problem of diminished apparent size is probably even more easily related to aircraft landing approaches. When accommodation is drawn toward the windscreen distance rather than toward the runway, the runway would appear smaller (and further). The probable response would be to carry more power to the runway, round out high, and land long and hard. Although this pattern is not necessarily related to the Mandelbaum effect in all cases, it would be relatively simple to determine the occurrence of this type of shift in operational settings or simulations. The accuracy of accommodation is also affected by

several factors that may exacerbate this problem, e.g., empty visual fields, lowered illumination, vestibular stimulation, stress, and fatigue.

The finding of both hyperopic (albeit relatively small) and myopic shifts and the concomitant verbal judgments of larger and smaller apparent size raises additional questions. If a pilot breaks out below the clouds and immediately is confronted with a clear view to the runway, the runway should exhibit some immediate change in apparent size. In this case the apparent size of the runway would appear to increase at a rate far greater than would be expected for the normal approach. In a situation where the pilot is already low and slow, an inappropriate response of attempting to pull up may stall the aircraft short of the runway. In other cases frequent reference to the instruments might lead to the same shift from near-to-far accommodation or in other cases where the windscreen has sufficient texture make it difficult to refocus to the external scene.

The quantitative shifts in apparent size that occur with accommodation were as consistent as the verbal judgments. Although the thrust of this research was to look for decreased apparent size and the converse was not investigated, one can infer from the verbal judgments that the increases in apparent size that do occur are also measurable. The practical significance of shifts in apparent size is difficult to determine. Although the actual magnitude of the shifts was quite large, the relationship between shifts in apparent size has been only recently

investigated in anything resembling an applied setting. Randle, Roscoe, and Pettit (in press) recently completed a study in which changes in accommodation were shown to be related to judgments of the accuracy of simulated aircraft landing approaches. By analogy, the Mandelbaum effect should be expected to generate similar data.

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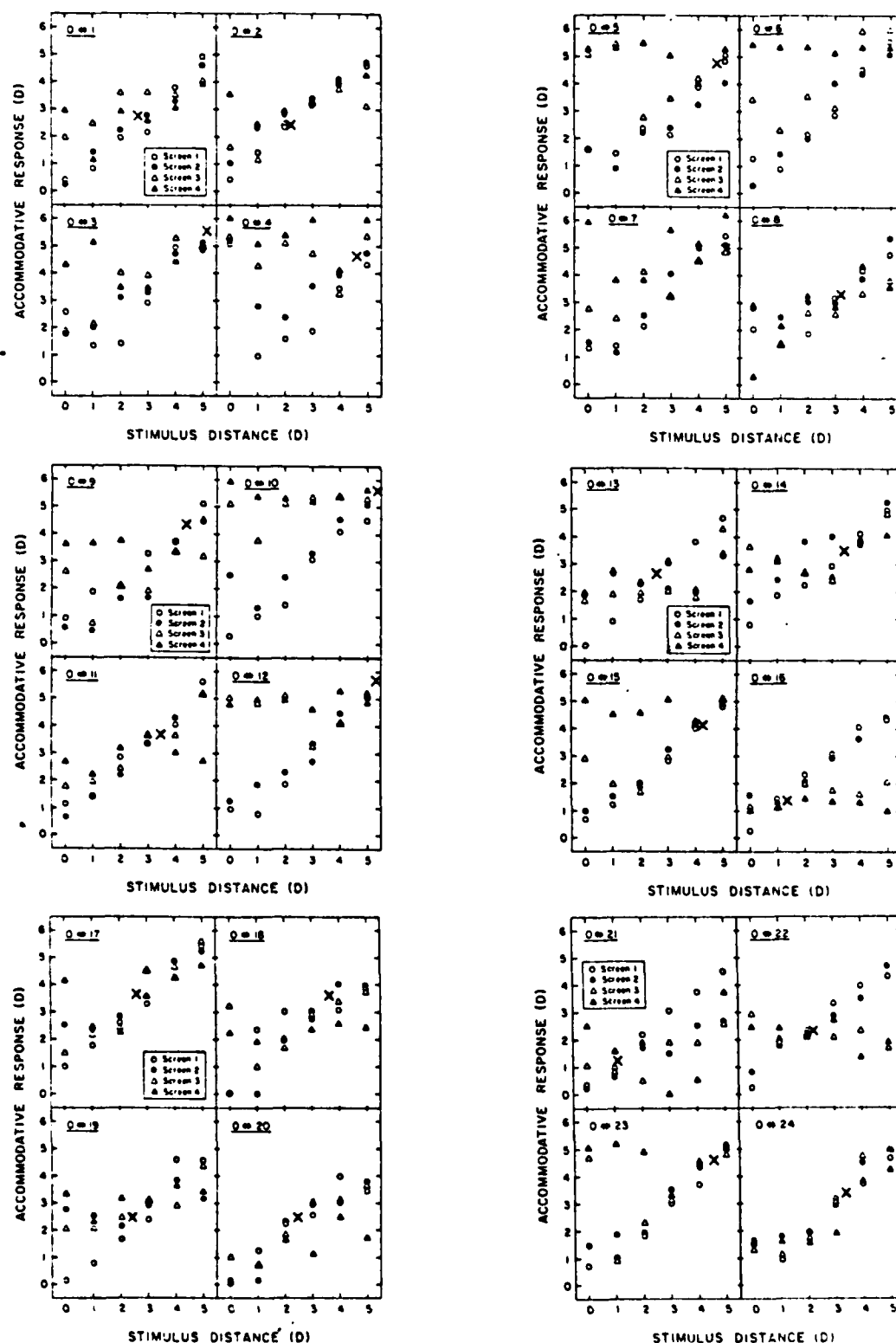
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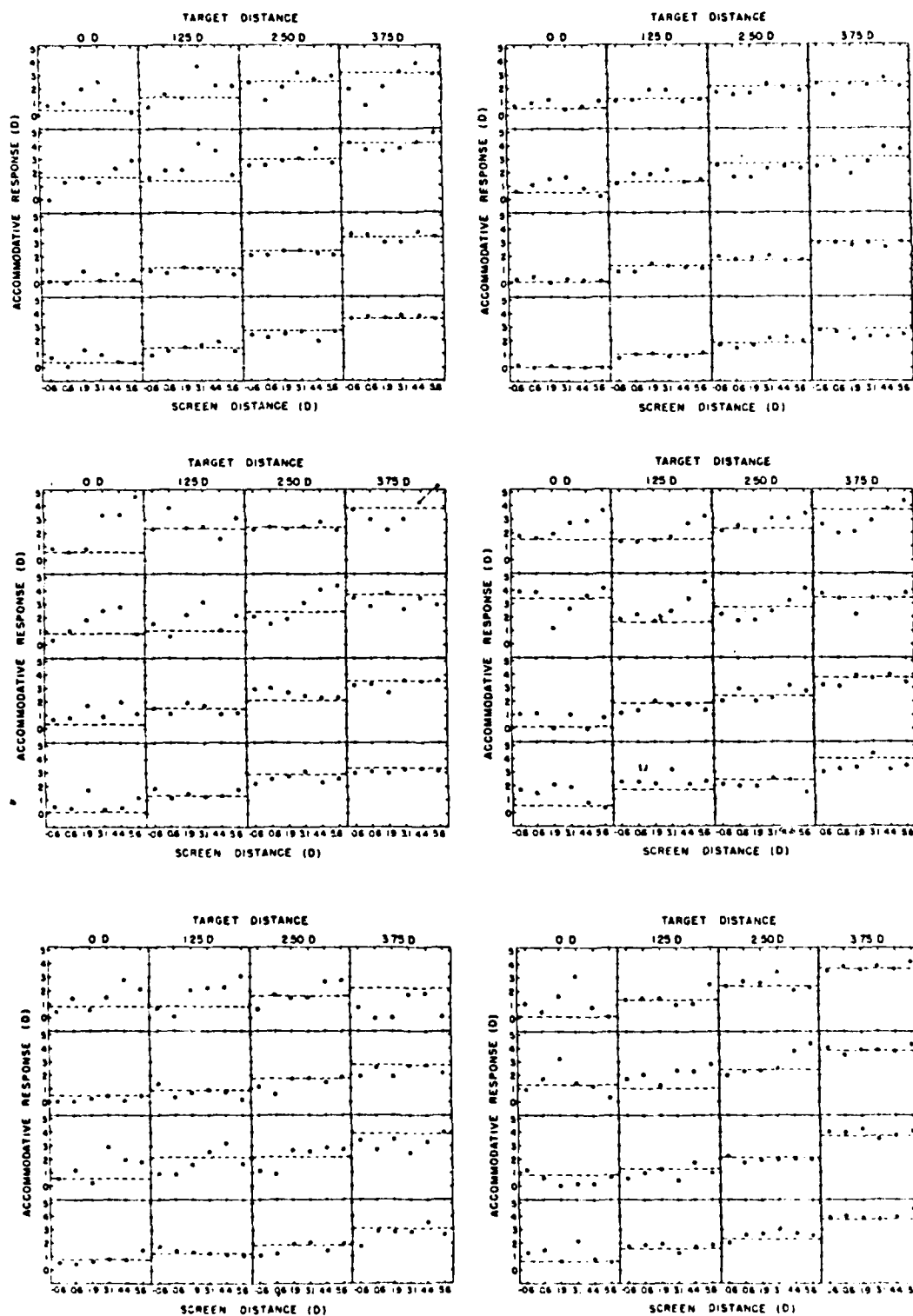


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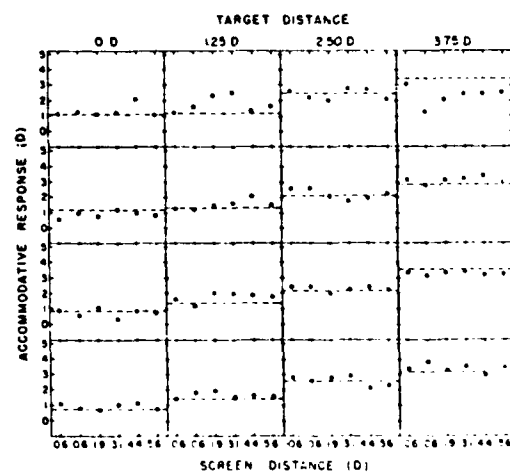
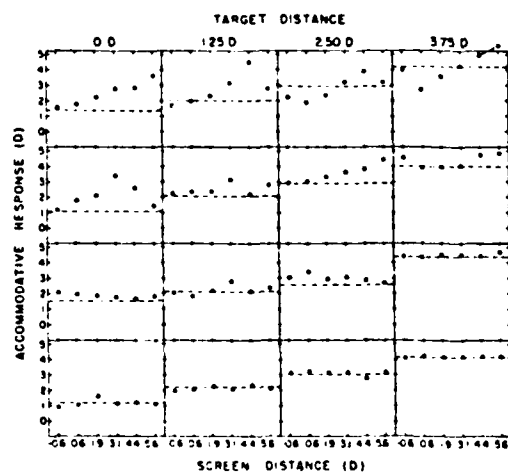
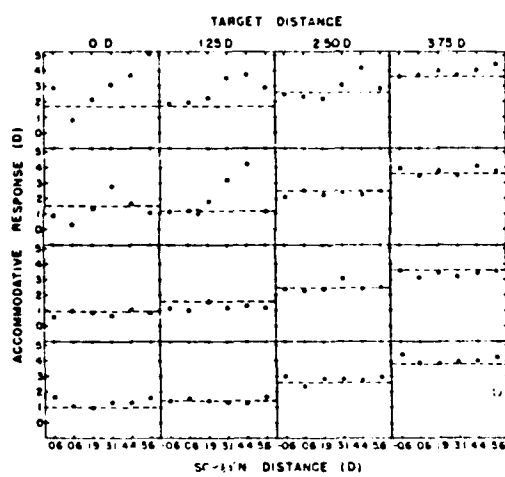
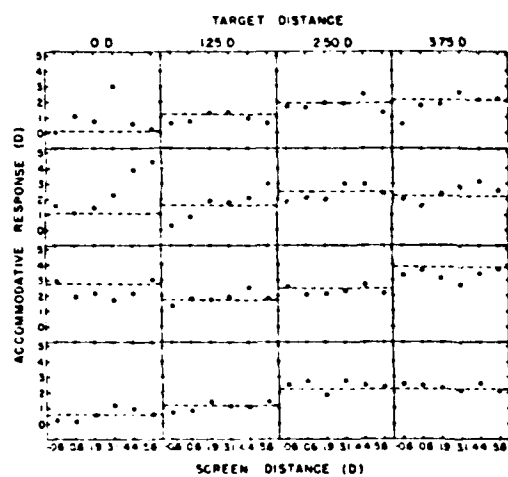
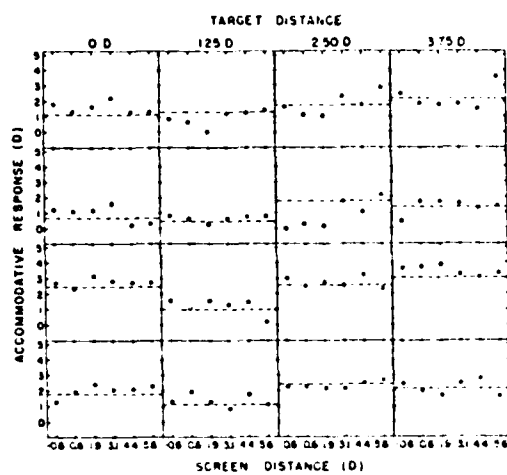
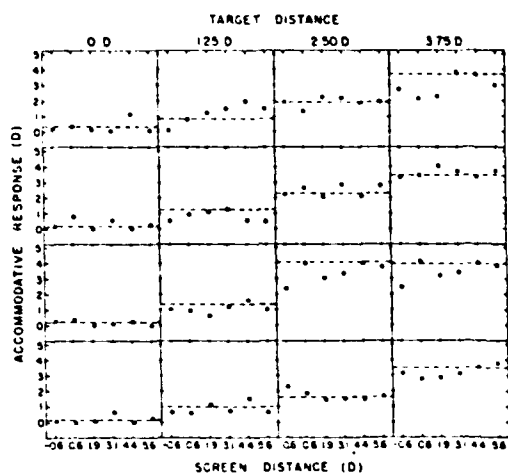
APPENDIX A: Individual Data for Observers From Experiment I. The X indicates the position of the observer's dark focus (without the right eye illuminated).



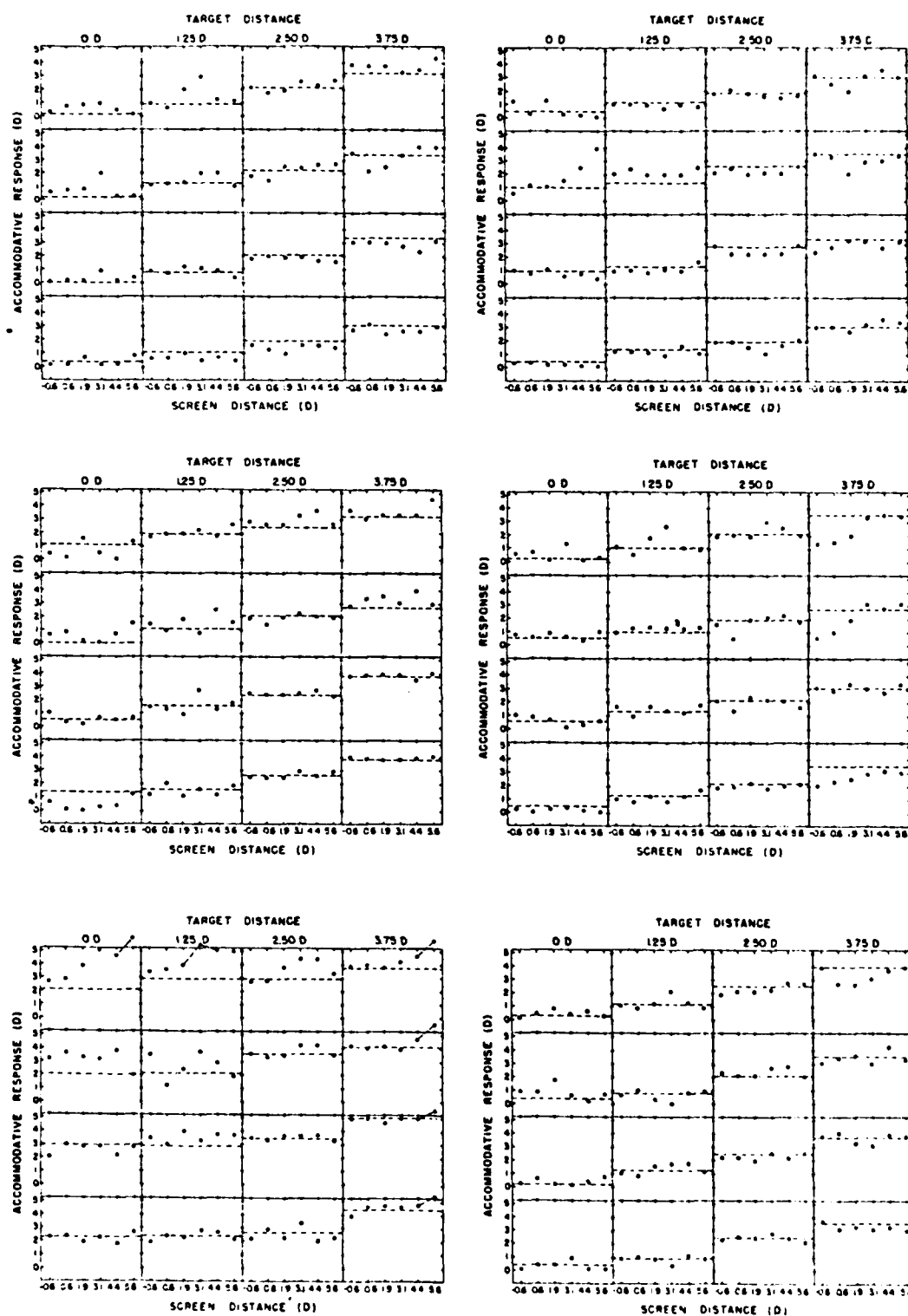
APPENDIX B: Individual Data for Observers 1-24 from Experiment II.  
Dashed horizontal line represents observer's response  
to target viewed without screens; Subjects 1-6.



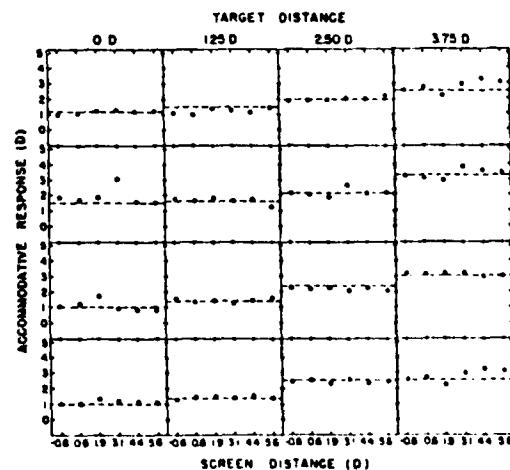
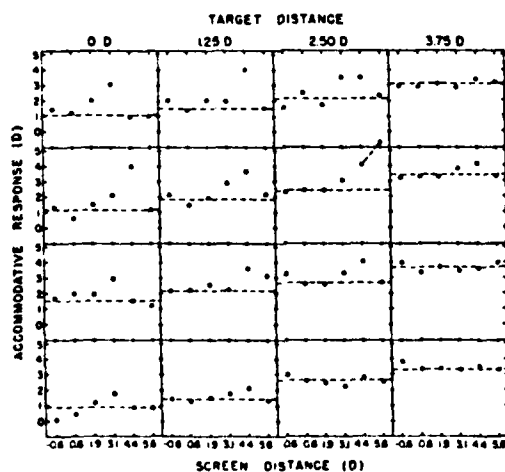
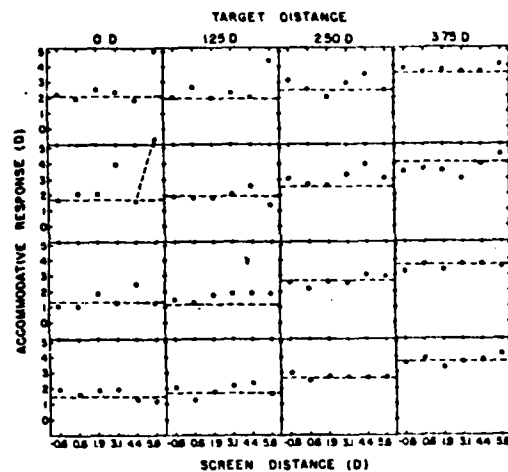
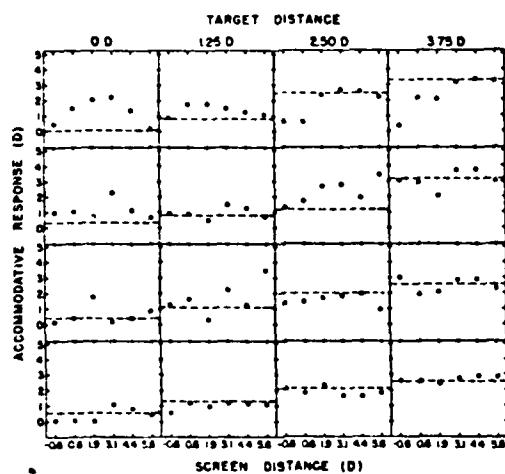
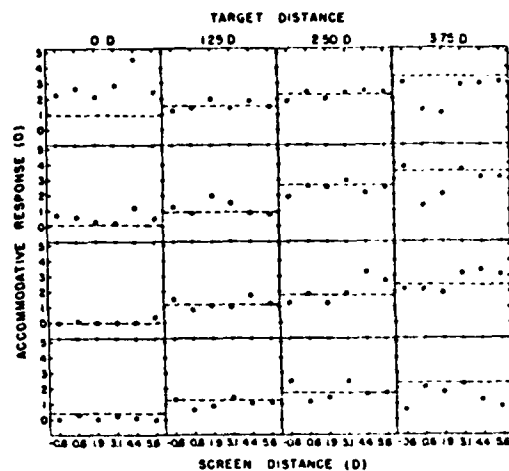
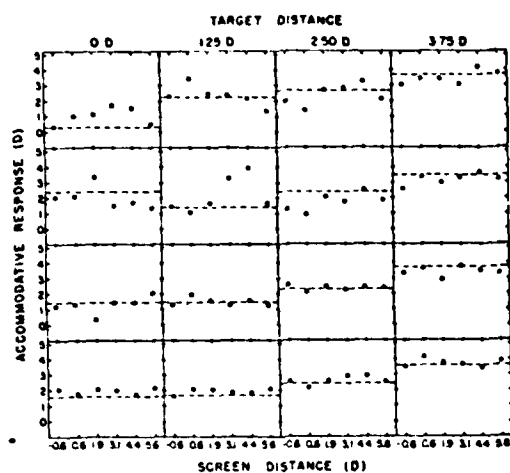
## APPENDIX B: Continued; Subjects 7-12.



## APPENDIX B: Continued; Subjects 13-18.



## APPENDIX B: Continued; Subjects 19-24.



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